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CROSS CHAIR

Exploration on Linoleum's Application in Furniture Design

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Master Thesis
2019

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CONTENT

ABSTRACT

Made of natural ingredients, linoleum is an environmentally sustainable surfacing material with unique aesthetic and tactile properties. Although it has been applied in furniture design since the 1930s, it's mostly applied on a flat surface such as the table top. There is very rare exploration into the techniques and various possibilities of linoleum in furniture design. The thesis aims to further explore the material structure of linoleum and its application in furniture design.

The literature review includes research into linoleum's manufacture, characteristics and its application in furniture design. The thesis project mainly uses hands-on experimenting, iterative testing and prototype making methods. During the experiment process, different carrier materials and various techniques are used. As wood and metal are two of the materials mostly used in furniture design, they are used as the primary carrier materials of linoleum in most of the tests.

The exploration aims to create various standard elements with a large variety of combination possibilities that could be applied in different furniture construction. The semi-tube material structure laminated by linoleum and veneers is found to be both lightweight and strong in construction, which resembles the bamboo material structure. Developed further from the semi-tube material structure, cross structure is even more stable so it's chosen to be the main structure of easy chairs. Named after CROSS CHAIR for the cross structure of semi-tubes, two chair prototypes made are stable in structure and stylish in form. This practice-led research illustrates linoleum's unseen possibilities in furniture design.

INTRODUCTION

My first contact with linoleum was in the Furniture Design MA course Form and Function in collaboration with Forbo Linoleum and Artek. Linoleum is an all-natural, tactile and durable composite, an environmentally friendly surface choice for furniture design. Although it has been used in furniture design since the 1930s, it's mostly used on the flat surface and attached to wood due to its material characteristics. During the exploration process, the semi-tube material structure in the shape of the tube split into a half laminated by linoleum and veneers was found to be lightweight and strong. The semi-tube shape resembles the bamboo structure that has been used in furniture design for quite a long time in Asian countries. The linoleum-veneer semi-tube material structure was used as the basic element in the design of a coat rack. It was exhibited in Artek Flagship Store during 2018 Helsinki Design Week and Greenhouse during 2019 Stockholm Furniture & Light Fair. The positive feedback from the public during exhibitions and the interesting exploration process motivated me to explore further into linoleum's application in furniture design.

While there have been previous furniture design works that use linoleum as the surfacing material mainly on the flat surface, exploration is very rare concerning various possibilities of linoleum. Moreover, there is very little literature that introduces linoleum's application and practical issues in furniture design. Therefore, it's meaningful to address how linoleum could be used in furniture design and the relevant practical issues to apply linoleum. The exploration process helps me learn how to develop structural elements for furniture design from material. The thesis project aims to explore various possibilities of linoleum and its application in furniture design with the methods of hands-on experimenting, iterative testing and prototype making.

The thesis starts with the background research into linoleum's manufacture and the situation of its application in furniture design. Preliminary tests are meant for introducing creation of semi-tube material structure by laminating linoleum and veneers. Further tests are done to explore various possibilities of linoleum with different carrier materials and techniques. Among the standard elements created by the further tests, the cross structure by inserting two semi-tubes crosswise is both lightweight and stable for furniture construction. It's used in the design of easy chair and two prototypes are made with the semi-tube cross structure.

Background Research

Manufacture of Linoleum

Linoleum is basically manufactured through mixing, pressing and a curing or drying process that takes several weeks — like a slow baking process (Stelmack, Foster & Hindman, 2014). The ingredients (Figure 1) include linseed oil, natural resins, sawdust, lime powder and natural color pigment (Peters, 2011), which are all natural nontoxic materials available in great abundance. Linoleum was originally used on floor and furniture linoleum was later developed from it.

2mm thick furniture linoleum is composed of 3 layers (Figure 2). Linoleum is covered with thin water-based cross-linked finish. The main difference from floor linoleum is that furniture linoleum has a layer of 1 mm thick paper underneath that makes it convenient to combine with other materials.

Characteristics of Linoleum

Linoleum was first manufactured in the mid-1800s in England (DeMouthe, 2005). It is a highly durable, environment friendly, resilient material that is used mainly for flooring (Kubba, 2012). Characteristics of linoleum are listed in the following.

- It requires less energy and creates less waste in its manufacture, and it can be chipped and composted at the end of its useful life (Kubba, 2012).
- Its natural bactericidal and antistatic properties help control dust and dirt and the subsequent growth of household mites and bacteria (Kubba, 2012), especially suitable with high hygienic requirements.
- Given its high resistance to oils and fat and the fact that is also slightly anti-bacterial, linoleum is very durable (Peters, 2011), often lasting for 25 to 40 years (Kubba, 2012). It's easy to clean.
- It is resilient, quiet and comfortable (Kubba, 2012).
- It has resistance to cigarette burns and favourable reaction to fire (Moro, 2016).
- There are many colors and patterns to choose from (Figure 3).


Figure 1. Raw materials of linoleum.

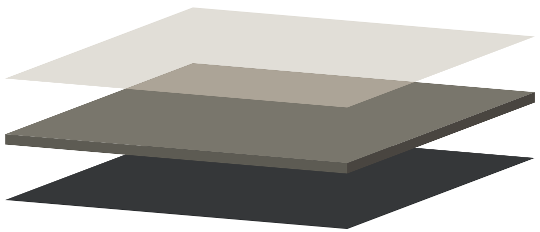


Figure 2. Material structure of linoleum.


Figure 3. Colorful linoleum samples.

It is also used on the furniture surfaces such as desks and countertops. Except for what's mentioned above, the reasons why linoleum is a good surface choice for furniture design are listed in the following from "Forbo Furniture Linoleum" (n.d.) official website.

- It's naturally flexible and could be applied easily to gently curved surfaces (with a maximum bending limit)
- It delivers a combination of a satin matt surface with fine texture, which gives warm tactile feeling.
- The natural surface has an earthy, solid quality and doesn't show fingerprints.
- Furniture Linoleum can be milled and shaped like wood and, for edge solutions, it can be combined with other materials

Application of Furniture Linoleum

There is no literature indicating the earliest time when linoleum was used in furniture design. However, some of the vintage furniture pieces found online show that early in the 1920s some designers / design brands started to apply linoleum on the furniture surface for its excellent properties. Some of the furniture pieces using linoleum as the surfacing material are shown from Figure 4 to Figure 10.

Figure 4. Bauhaus B9 Nesting Tables with tops in linoleum, designed by Marcel Breuer in 1920s.

Figure 5. Artek Tea Trolley 901 with top and shelf surface in linoleum, designed by Alvar Aalto for Artek in 1936.

Figure 6. Artek L-leg Furniture Collection with table tops and seats in linoleum, designed by Alvar Aalto for Artek between 1933-1956.

Figure 7. Dutch Coffee Table with table tops in linoleum, designed by Willem Hendrik Gispen for Gipsen in 1950s.

Figure 8. Neighbourhood Chair with the backrest and seat upholstered in linoleum, designed by Alex Swain for ByALEX.

Figure 9. Bac Chair with backrest and seat in linoleum, designed by Jasper Morrison for Cappellini in 2009.

Figure 10. EM Desk with top coverd by linoleumby Örn Duvald in 2017.

As it’s seen from the design examples, furniture linoleum is mostly used on the flat surfaces such as trolley shelf, desktops and countertops or on gently curved surfaces such as Neighbourhood Chair and Bac chair. It might result from the original function of linoleum for the floor as well as the physical characteristics of linoleum itself. Due to the material structure (Figure 2) and manufacturing process, linoleum has some flexibility but it has the bending limit of Φ50mm according to the Forbo Linoleum Installation Instructions. Moreover, bending linoleum is usually regarded as one way of edge finishes (Figure 11) instead of an essential part in furniture design. Therefore, furniture linoleum is mostly used on the flat surfaces or gently curved surfaces.

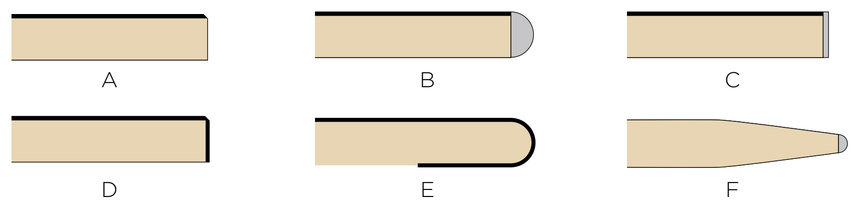


Figure 11. Different edge finishes of linoleum

Starting Point

As furniture linoleum is mostly used on the flat surfaces, I was curious how it would be to apply linoleum on the sharply curved surface at the beginning of the Furniture Design MA course Form and Function collaborating with Forbo Linoleum and artek in 2018. The course required to use wood as the carrier material of linoleum. Made from all natural ingredients and covered with thin finish, linoleum has satin matt surface with fine texture and gives warm tactile feeling, which is similar to wood. When linoleum is applied on the flat surface of wood, the beauty of linoleum and wood seem to be separate. A question arose in my mind, "how to manifest the beauty of wood and linoleum integrally?" I had the ideas of making semi-tube[1] and half-cylinder by wrapping linoleum around wood (Figure 12). The idea of semi-tube shape was inspired by the bamboo structure that also has two different visual effects and tactile feeling after being split into halves (Figure 13). In this way, the beauty of linoleum and wood are dynamically visible at the same time from different angles.

I started to search for more information about it. Forbo staff Marijke Griffioen introduced us some of the samples made by design students while in collaboration with HDK in Sweden. I was impressed by Rob Curran's works of wrapping linoleum around solid wood rods (Figure 14), which shows linoleum's pliability. And it's closely related to my ideas. I got to know some tips through email (personal communication, April 17, 2018) from Rob Curran who had already done some tests on bending linoleum.

"Depending on the radius of the wood you want to laminate, the different colours of linoleum react differently. Some cracks on the surface after the process. A bigger diameter is better, 25-30 mm or greater.

You have to place the linoleum in boiling water for an hour or so. While it is still wet, try and remove the paper backing. It doesn't have to be perfect and you can leave a little on it. This helps when gluing. Removing the paper reduces the thickness of the material when wrapping it around a rod. It makes it easier.

I applied just ordinary white wood glue to the back of the linoleum and rolled it around the rod. Wrapping lots of masking tape around the whole thing to keep pressure on it while it dries. It's possible to clamp a length of wood along the seem to hold it down while it cures."

The process of how Rob Curran made the samples is very inspiring for realization of my ideas. Moreover, it's said in the Forbo Furniture Linoleum Instructions that linoleum could be bent with the machinery used to bend HPL[2] but the temperature needs to be under 70 °C. It indicates that heat and force could help bend linoleum, which verifies Rob Curran's narration about the pre-treatment of linoleum from another aspect. It also reminds me of the compression moulding techniques of laminating veneers into molded plywood. For the production of molded plywood several veneer plies are glued together crosswise under heat and pressure and shaped two or three-dimensionally in press machines (Glasner, B. & Stephan O, 2012).

One way of making prototypes at school is to add external force to the mould and veneers with vacuum bag system at around 60 °C for over 1.5 hours so that the urea resin adhesive can dry and harden. The material structure of semi-tube is easier to make by laminating linoleum and veneers with the mould compared to half-cylinder. Therefore, I decided to take some preliminary tests on the semi-tube material structure first.

1 Semi-tube refers to the tube shape that is split into a half.

2 HPL refers to High Pressure Laminate, a durable decorative surface material that is made with paper and resin under heat and pressure.

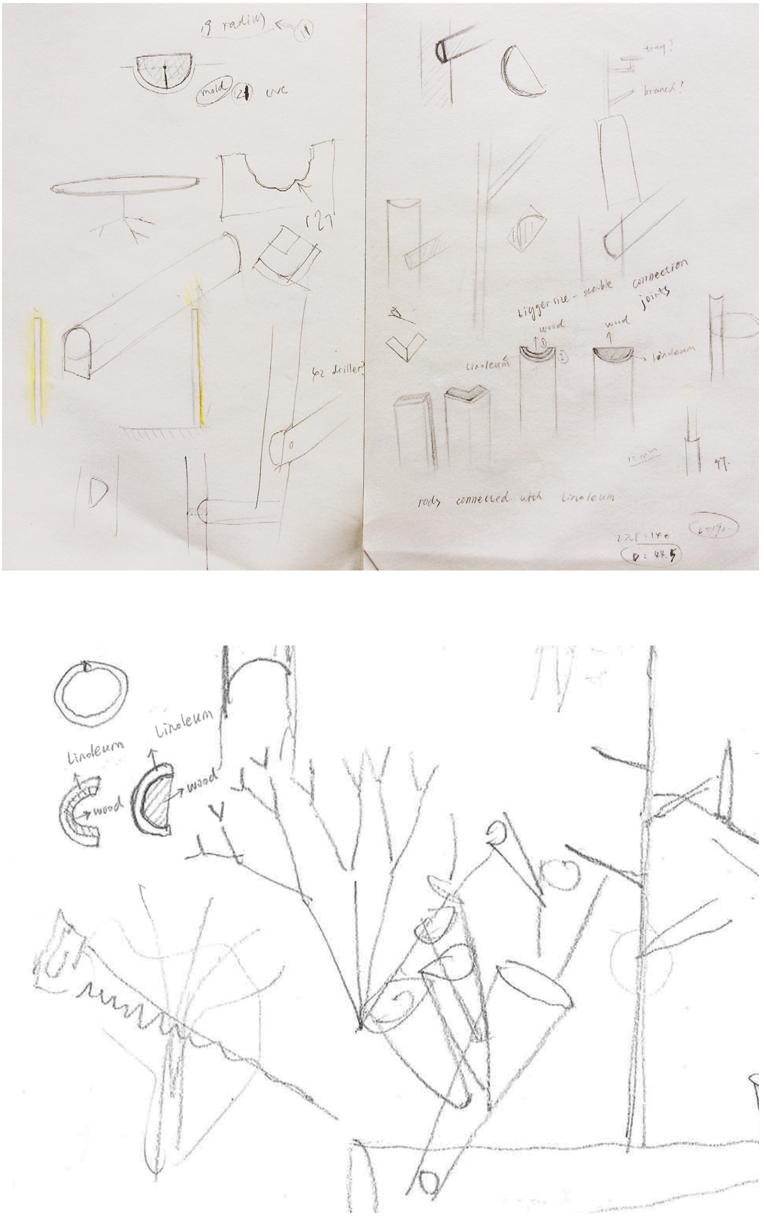


Figure 12. Drafts about semi-tube and half-cylinder material structure.

Figure 13. Bamboo split into halves.

Figure 14. Pine rods wrapped by linoleum designed by R. Curran.

Preliminary Tests on Semi-tubes

First Test

The first test taken was an initial step to test if linoleum and veneers could be glued with urea resin adhesive and could remain uncracked with the 36 mm mould edge after being heated for 1.5 hours at 60 °C.

8 layers of 1 mm thick veneers, 3 layers of 0.6 mm thick veneers and 1 layer of 2 mm thick linoleum were overlaid (Figure 15). The linoleum wasn't neither soaked in hot water nor taken away the paper backing as mentioned by Rob Curran in order to see furniture linoleum's original characteristics. After applying urea resin adhesive, they were put into the rubber vacuum bag in the oven. After being heated at 60 °C for 1.5 hours, the urea resin adhesive became dry and hard. All the veneers and linoleum were combined tightly into a semi-tube material structure which was very strong yet quite light (Figure 16). And both linoleum and the veneers didn't crack in this test. The first test shows that linoleum could be glued to veneers with urea resin adhesive after being heated for 1.5 hours at 60 °C. It also indicates that linoleum without any pretreatment has some pliability and the semi-tube material structure is suitable as the stable and rigid part of furniture.

The material structure of semi-tube resembles that of bamboo. Bamboo has extreme bending strength and a tensile strength while its hollow interior makes the material highly elastic and light (Peters, 2011). The linoleum-veneer semi-tube material structure also has a hollow interior and it's very light. Since the materials are combined with hardened urea resin adhesive, the semi-tube material structure isn't elastic like bamboo but it has very high tensile strength and compressive strength instead. It has been a long time since bamboo was used to make household goods and furniture, which could be inspiring for applying the linoleum-veneer semi-tube material structure to furniture design.

Figure 15. The mould with 36 mm edge and materials for the first test.

Figure 16. The mould with 36 mm edge and materials for the first test.

Controlled Tests on Semi-tubes

The first test verifies feasibility of laminating linoleum and veneers into semi-tube material structure under certain conditions. But more tests needed to be done and compared with different variables to see how the strength of the semi-tube material structure would change and how the surface would react. The controlled tests on semi-tubes would help find out how to apply linoleum on curved surface in a proper way. The variables include different layers of veneers, mould profile shapes, linoleum bending diameters, linoleum colors and if the linoleum has the pretreatment. More detailed description of the variables is listed in the following.

Layers of veneers:
Different layers of veneers might influence the strength of semi-tubes. To improve the strength of veneer-laminated plywood, veneers of odd numbers are always put crosswise. The wood grain of 1mm thick veneers follows the extension direction of the mould while 0.6 mm thick veneers are put crosswise in between to avoid the veneers from cracking.

Mould profile shapes:
The shapes of mould profile are either in C shape or in U shape (Figure 17). Different mould profiles might affect the linoleum surface and the composite strength differently. The edge diameter of both moulds is 19 mm (the radius is 9.5 mm). The C profile mould is 19 mm wide and the U profile mould is 38 mm wide.

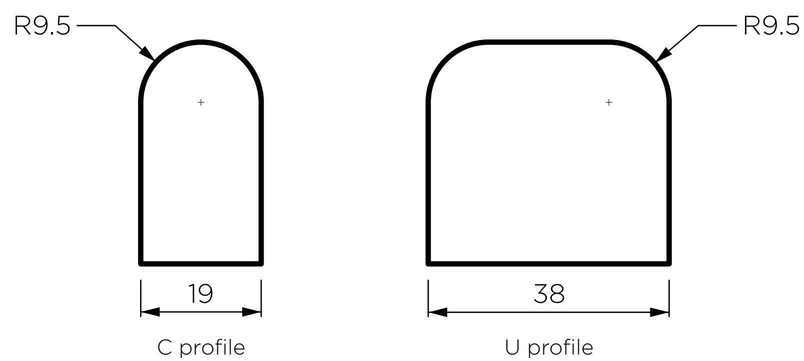


Figure 17. Mould profiles in C shape and in U shape.

Linoleum bending diameters:
It's undoubted that smaller bending diameter would make linoleum surface crack more easily. The bending diameter results from the mould edge diameter and the thickness of veneers. With the fixed diameter of mould edges, using more layers of veneers amounts to bigger bending diameter of linoleum. Considering the experiment efficiency, the influence of linoleum bending diameter is verified by comparing the tests with different veneer layers and the same mould edge diameter instead of making the moulds of different edge diameters. As in the first test mould edge diameter is 36 mm, a smaller edge diameter should be tested. Therefore, the diameter of all the mould edges is 19 mm.

Linoleum colors:
As mentioned by Rob Curran (personal communication, April 17, 2018), depending on the radius of the wood you want to laminate, the different colours of linoleum react differently. With the mould edge of small diameter, linoleum colors might influence the linoleum surface. Therefore, three colors (Figure 18) from Forbo Linoleum are chosen for testing including dark colors Black (4023 nero) and bright colors Red (4164 salsa) and Blue (4181 midnight blue).

Linoleum pretreatment:
Linoleum pretreatment refers to soaking linoleum in hot water for about an hour before removing the paper backing of linoleum. Linoleum pretreatment might help increase pliability of linoleum and prevent the surface from cracking when the mould edge diameter is small.

Figure 18. Linoleum of three colors chosen for testing.

The constants in all the controlled tests include one layer of linoleum, urea resin adhesive to be applied, vacuum bag system, heating temperature, heating time, composite length and height. After applying adhesive, veneers and linoleum are fixed to the mould with tapes, put inside the vacuum bag and heated for 1.5 hours at 60 °C. The semi-tube composites are all cut into the shapes with the length of 230 mm and the height of 35 mm. The test results would be analyzed from two aspects, compressive strength and surface condition of linoleum. The surface condition of linoleum is either cracked (Figure 19) or fine (Figure 20). "Fine" means that the surface is undamaged and it remains in the same condition as before the test.

Table 1. Tests on linoleum-veneer semi-tubes.

Test No.	Linoleum Color	Pretreatment	Layers of 1 mm veneer	Layers of 0.6 mm veneer	shape of mould profile	Surface of linoleum
01	Black	No	2	1	C	Cracked
02	Black	No	3	2	C	Cracked
03	Black	No	4	3	C	Cracked
04	Black	No	6	3	C	Fine
05	Black	No	3	2	U	Fine
06	Black	Yes	3	2	C	Fine
07	Black	Yes	3	2	U	Fine
08	Red	No	3	2	C	Cracked
09	Red	No	3	2	U	Cracked
10	Red	Yes	3	2	C	Fine
11	Red	Yes	3	2	U	Fine
12	Blue	No	3	2	C	Cracked
13	Blue	No	3	2	U	Cracked
14	Blue	Yes	3	2	C	Fine
15	Blue	Yes	3	2	U	Fine

Figure 19. Cracks on the linoleum surface of semi-tubes.

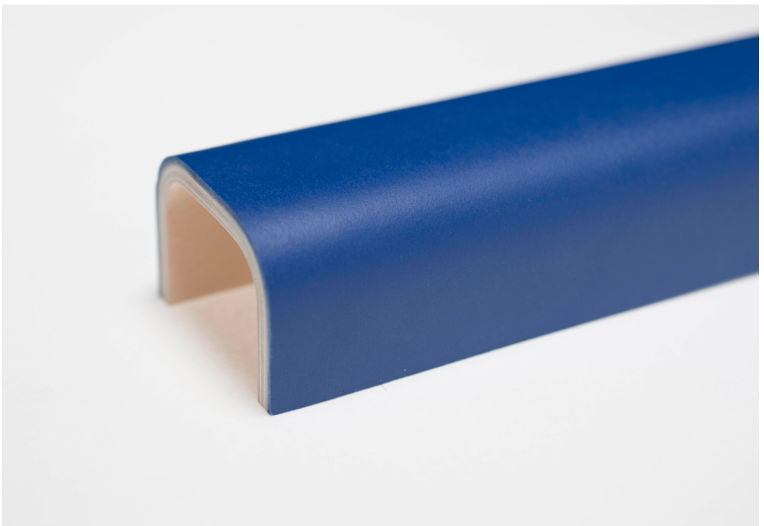


Figure 20. Fine surface of the linoleum.

Table 1 shows the details of all the controlled tests. There are several findings in this series of tests (Figure 22). The findings are mainly about the influences of different variables on the semi-tube material structure's compressive strength and linoleum surface.

Compressive strength

(1)
Compressive strength in vertical direction is better than that in horizontal direction (Figure 21) for every testing piece. Based on mechanical analysis, the compressive strength in the horizontal direction of semi-tube in U profile should be larger than that in C profile although they were quite similar in the controlled tests No.02 and No.05, No.06 and No.07.

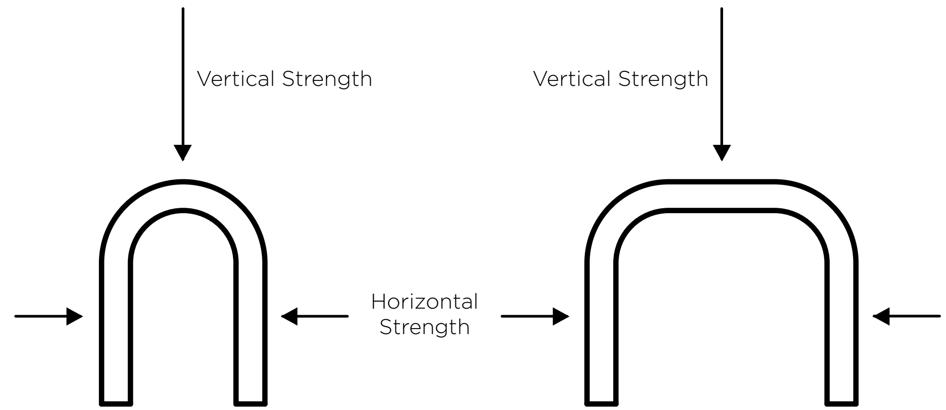


Figure 21. Compressive strength in different directions.

(2)Compressive strength: 04 > 03 > 02 > 01
Although more layers of veneers used make the bending diameter bigger, the main influence on the strength should be the thickness of the semi-tube due to the veneer layers. Comparison from Test No.01 to Test No.04 shows that more layers of veneers especially 1 mm thick veneers could make the semi-tube material structure stronger.

(3)
Contrast between Test No.02, Test No.08 and Test No.12 shows different

colors of linoleum don't exert influence on the sample's compressive strength.

Contrast between Test No.02 and Test No.06 shows pretreatment doesn't exert influence on the sample's compressive strength.

Linoleum surface

(4)
Contrast between Test No.02 and No.05 shows that the mould profile shapes would affect linoleum's surface. Using the C-profile mould would make the surface crack more easily than using the U-profile mould under the same conditions.

(5)
Using more layers of veneers amounts to bigger bending diameter of linoleum. Therefore, comparison among Test No.01 to Test No.04 shows that smaller bending diameter would make linoleum surface crack more easily.

(6)
Comparison among Test No.05, No.09 and No.13 shows that linoleum of bright colors is easier to crack than that of dark color such as black under the same conditions. Different color pigment has influenced the physical characteristics of linoleum.

(7)
Contrast between Test No.02 & No.06, Test No.08 & No.10, Test No.9 & No.11, Test No.12 & No.14, Test No.13 & No.15, shows that soaking linoleum in hot water and taking away the paper backing could help solve the problem of cracking. Pretreatment of linoleum helps increase linoleum's pliability and prevent the surface from cracking.

The tests verifies more layers of veneer could increase the compressive strength of semi-tubes and pretreatment or linoleum colors doesn't exert influence. The tests also verifies that the mould profile shapes, linoleum bending diameter, linoleum colors and pretreatment would influence the surface of linoleum. Pretreatment of soaking linoleum in hot water and taking away the paper backing could help solve the problem of cracking when the mould edge diameter is small or the linoleum color is bright. These preliminary tests help find out how to apply linoleum on the curved

surface in a proper way. Apart from these findings, a breakthrough is made in applying linoleum on the mould edge of 19 mm that is much smaller than the bending limit of 50 mm indicated in the Forbo Linoleum Installation Instructions. Both C-profile and U-profile semi-tubes laminated with 3 layers of 1 mm veneers, 2 layers of 0.6 mm veneers and 1 layer of linoleum have good strength to be structural elements of furniture as long as pretreatment is done to prevent linoleum from cracking.

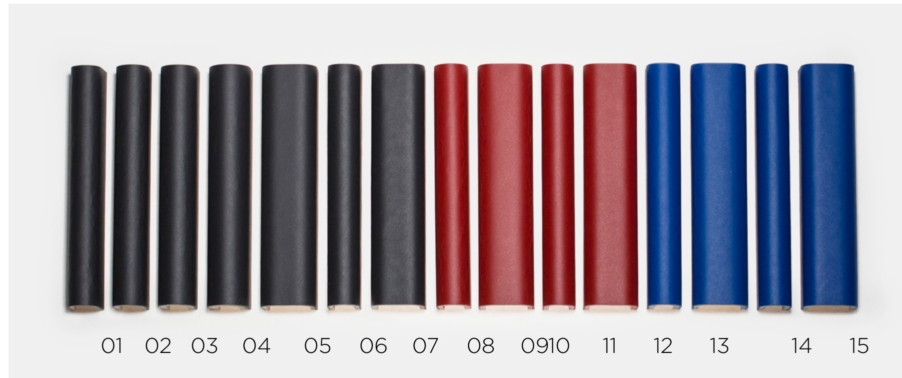


Figure 22. A series of controlled tests on semi-tubes.

Semi-tube Arc Tests

The semi-tubes are both strong and light and deserve further exploration and development. In order to find out more possibilities of this material structure, more complex moulds based on semi-tube were also developed for testing. One of the moulds formed a semi-tube arc (Figure 23) that has very good compressive strength at both sides and flexibility in the middle part. It is inspired from the traditional bamboo covering techniques and its application on furniture design such as stool, armchair and table for a long time (Figure 24). Figure 25 shows the details of bamboo covering technique. The bamboo is heated after cutting and digging in order to make bending easily (Figure 26) and keeping the bent shape after cooling down, which is a step of the bamboo covering techniques ("Bamboo Covering", n.d.). The linoleum-veneer semi-tube arc was formed by laminating linoleum and veneers with compression, heat and hardened adhesive. Similar to bamboo material structure, the semi-tube arc has some elasticity in the middle part and compressive strength at both sides. The semi-tube arc was later developed into a coat hanger with modified mould and refining techniques (Figure 27).

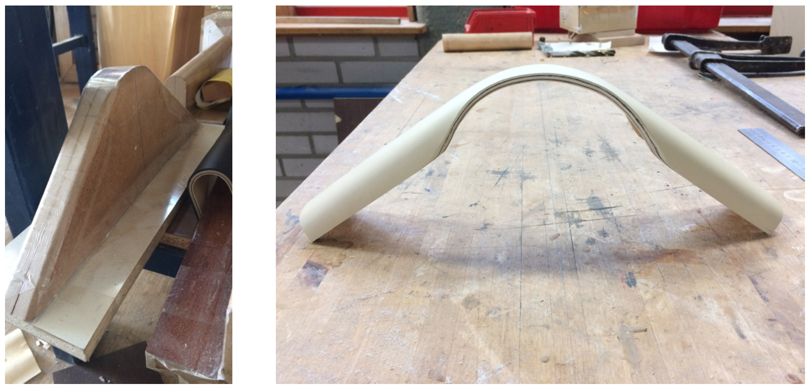


Figure 23. The semi-tube arc mould and test sample.

Figure 24. An ordinary bamboo stool that uses bamboo covering techniques in China.

Figure 25. The details of bamboo covering techniques.in China.

Figure 26. Digging and heating bamboo to bend the bamboo.

Figure 27. Coat hanger body in the semi-tube arc shape.

Coat Rack Design

Since the material structure of semi-tube structure has very good compressive strength and tensile strength, it's very suitable to be the element of racks. Inspired by how bamboo covering techniques made use of bamboo's elasticity, I had the idea of making a coat rack with the linoleum-veneer semi-tube arc and semi-tube. The semi-tube arc could be developed into the leg frames of the coat rack and the cross bar for hanging could be made with a straight semi-tube. As the middle part of the semi-tube arc has some pliability, it could clamp or hold the cross bar. Figure 28 shows the drafts of different coat rack ideas. Considering structural stability of coat rack, the idea of clamping the cross bar with semi-tube arc was developed further and a corresponding 3D model was drawn in the computer (Figure 29).

However, the mould made for the semi-tube arc that is high up to 1.52 meters was found too high to fit into the vacuum bag. When the size became much bigger, the difficulty of realization also increased a lot accordingly. Moreover, it was worrying that the middle part of the arc was not in semi-tube shape and the strength was not enough. As an important part that connects with the cross bar, the middle part of the arc might be too weak to bear the load from hanging stuff on the cross bar.

Therefore, I started to think of only using the straight semi-tube material structure as the basic element of coat rack including legs and cross bar. What's more, simple and basic elements could make production easier and they might be able to compose other types of furniture to form a collection. The 1:1 partial mock-up (Figure 30) of the most important joint was made. The proportion was good in aesthetics but some details were reconsidered such as the bevel cut at the end of semi-tube and the connecting wooden block between vertical and horizontal parts.

During the process of making the 1:1 prototype, some problems occurred (Figure 31). For example, there was a bump on the surface which might result from the wrinkle of veneer after getting in touch with the wet adhesive for some time. It also happened that the cross section had curved veneer although the surface was very smooth. It's very important that after applying adhesive the veneers especially the thin ones are flat and there is no particles under the linoleum layer. However, it's still hard to avoid the flaws especially when the semi-tubes for the coat rack are so long compared

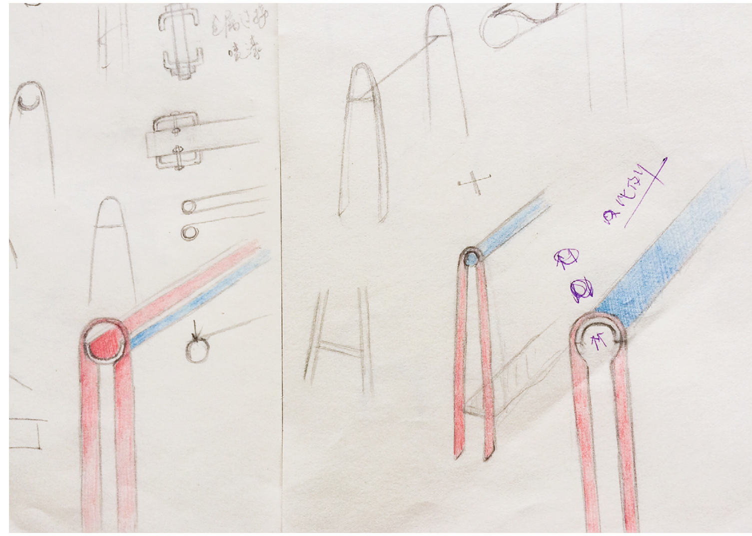


Figure 28. Drafts of the coat rack.

Figure 29. Digital rendering of the coat rack in computer.

Figure 30. The 1:1 partial mock-up of coat rack joint.

Figure 31. Bump on the leg surface and curved veneer in the cross section.

to the small test samples.

Due to the time limit, all the parts were glued in the first prototype. The first prototype (Figure 32 & 33) was exhibited in Artek Flagship Store during 2018 Helsinki Design Week and in Vitra Store in Amsterdam in 2019.

From the end of 2018 to February 2019, I further developed the structure and made a second prototype with the knock-down structure that is convenient for transportation. The knock-down structure is very simple but stable. The second prototype was exhibited in the Greenhouse section of 2019 Stockholm Furniture & Light Fair and earned high praise from the professionals. There are several brands including FUNCTIONALS from the Netherlands that are interested in mass producing it. The positive feedback from the public during exhibitions and the interesting exploration process motivated me to explore further into linoleum's application in furniture design.

Figure 32. Details of the coat rack and coat hanger prototypes.

Figure 33. The coat rack prototype.

Further Tests on Standard Elements

"As you know, you need a snail to make soup. And to make furniture you need a basic element, a structural standard part, which modified in some way, appears in all pieces. Apart from its structural characteristics, the basic element must have a purposeful and style creating form."

——Alvar Aalto's introduction to the catalogue of his exhibition at the NK department store in Stockholm in 1954 (Aalto et al., 1984)

Standard Elements

In the coat rack design, the semi-tube material structure is used as a basic element. It's not a new way of designing furniture. Instead, there are many classic collections that are constructed with basic standard elements. For example, one of the greatest Finnish architects and designers, Alvar Aalto, has designed three different furniture collections with L-leg, X-leg and Y-leg respectively. Aalto called a furniture leg "the column's little sister," because by discovering new leg constructions, he changed the style of his furniture just as clearly as the Doric, Ionic and Corinthian columns each resulted in a special order or style of architecture (Aalto et al., 1984).

L-leg

In the late 1920s, architect and designer Alvar Aalto began experimenting with bending solid wood in collaboration with furniture manufacturer Otto Korhonen (Artek, n.d.). One of the most important discoveries might be the idea of "bent knee", L-leg (Figure 34). The way how to make L-legs is ingenious. According to Alvar Aalto Foundation's description (n.d.), saw cuts are made in one end of the blank for the L-leg, thin pieces of wood inserted into the gaps with glue and then the wood is bent to a 90 degree angle using heat and steam. This way of bending solid wood simplifies the bending process and increases the stability of the component. Its system of standard components enabled the creation of more than 50 versatile products (Artek, n.d.). Figure 35 shows the furniture collection that uses L-legs including Aalto Table half-round, Aalto Table rectangular, Chair 65 and Stool E60.

Y-leg

Between 1946 and 1947, the Y-leg construction (Figure 36) was developed from the earlier invention of the L-leg. In the Y-leg, two slender L-legs were chamfered on opposite sides and glued together (Alvar Aalto Foundation, n.d.). A new collection of furniture constructed with Y-legs was launched. Figure 37 shows a Y-legged table with removable glass top.

X-leg

Aalto designed yet another L-leg variation in the 1950s, the ‘X-leg’ or the ‘fan leg’ that is a combination of five, thin, interlinked L-legs after sawing (Alvar Aalto Foundation, n.d.). Figure 38 shows the details of customized x-leg low table. X-legs were applied to a new series of furniture (Figure 39) including stools, tables and armchairs.

Summary

The furniture collections designed by Alvar Aalto are constructed on the standard elements which were created by his exploration of new techniques in bending and laminating wood. The standard elements endow furniture design with countless combination possibilities, creating “an uncompromising consistency of unforseen flexibility with regard to different functions and adaptation to various settings” (Artek, 1981). The invention process is similar to how I tested semi-tube material structure and used it in the furniture design as a basic element. In the preliminary tests, I found the influences of different variables on the strength of the semi-tube material structure and the linoleum surface. And a coat rack was constructed with the standard semi-tubes in both C-profile and U-profile. From the preliminary tests I’ve earned plenty of experience of applying linoleum and the relevant techniques of laminating veneers and linoleum.

But there are still plenty of possibilities of linoleum’s application on furniture, which deserves exploration from different angles. Moreover, the semi-tube material structure itself could have variants and combinations. The exploration process from material to basic element and its application to furniture design is very interesting for me. Therefore, further tests need to be taken with different carrier materials and techniques in order to discover more standard structural elements qualified for furniture design. As wood and metal are the materials mostly used in furniture design, they were used as the carrier materials in most of the further tests. Techniques such as compression moulding and 3D moulding were used in the tests of combining linoleum and wood. Common cold deforming techniques were used in the tests of combining linoleum and metal.

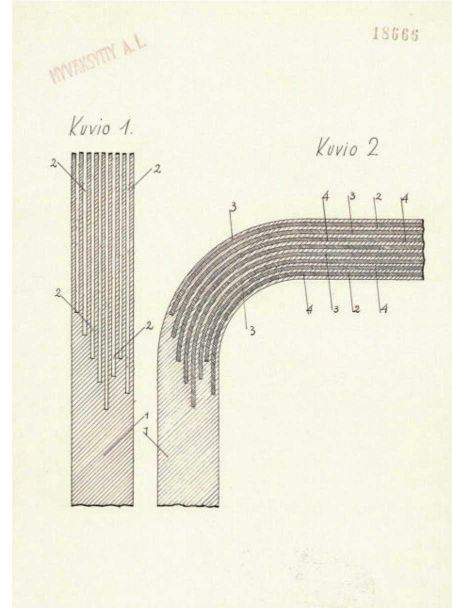


Figure 34. Patent 18666, a way of bending wood and manufacturing L-legs.

Figure 35. A furniture collection using L-legs.

Figure 36. Detail of Y-leg.

Figure 37. Glass table Y805 using Y-legs designed in 1947.

Figure 38. Details of customized x-leg low table.

Figure 39. Stools and table with X-legs.

From 2D to 3D (test group A)

The semi-tube material structure requires moulds, temperature control, vacuum bag pressure and long time preparation. It’s a quite complex process to make. Therefore, an idea came to my mind to combine linoleum with veneer into a flat sheet that is both flexible and stable. The composite sheet could form a 3D structure after being bent or connected.

In the test group A (Figure 40), a layer of 1mm veneer and linoleum were combined together with white wood glue and pressed for some time. It’s a flexible composite sheet but stronger than a single layer of veneer or linoleum. By inserting slots, different flat composite sheets could form various 3D structures but not in a delicate way due to its resistance to deformation. Using hardware to help form 3D structure might be workable, which needs further tests. The advantage of the composite sheet is that it could be flat-packaged and easy for transportation. However, the 3D structure formed by the composite sheet doesn’t have good compression strength and not suitable to be a component for furniture. It’s more likely to be a decorative component for homewares.

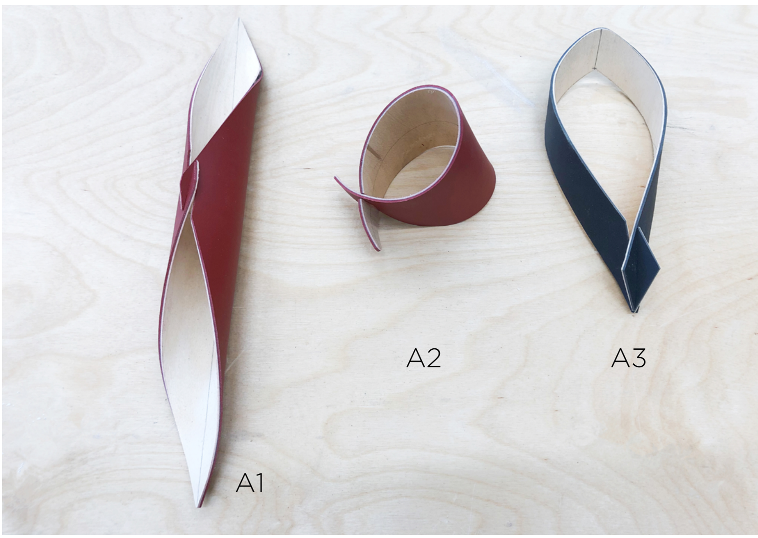


Figure 40. The 3D structures formed by the flat composite sheet of linoleum and veneer (test group A).

Metal as Carrier Material (test group B, C & D)

As the surface material, linoleum is always applied to a carrier material. On the back of furniture linoleum there is a paper layer that is absorbent to water like the most uncoated wood based panels, which might be one of the reasons why furniture linoleum is mostly applied to wood based panels. Moreover, the tactile finish and matt surface of linoleum matches well with the warm feeling of wood.

Except for wood, metal is also one of the most common materials used for furniture. Metal is easy for cold forming, which could save much time and energy. Metal sheet has very good structural strength compared to veneer sheet after deformation. As it’s mentioned in the Forbo Installation Instructions, furniture linoleum can be applied easily on all common materials including steel. But it’s very rare to see the furniture combining metal and linoleum. Therefore, it deserves to carry some tests to combine metal and linoleum.

Test group B

In the test group B (Figure 41), linoleum was glued to the metal sheet with contact adhesive. Then the composite was bent in different ways. The composite could be bent in a round shape with linoleum inside (sample B2). After being bent with sharp edges, the linoleum separated from metal (sample B1) at the edges. After being bent with the linoleum outside (sample B3), linoleum cracked on the surface. The failures might be caused by different ductility of metal and linoleum. Metal has better ductility than linoleum. When linoleum and metal are stuck together, tension develops between them. In the test sample B1 and B3, tension got bigger and linoleum either separated from metal or cracked on the surface.

Test group C

Different from white wood glue that needs at least half an hour to dry and pressure is needed for at least half an hour, contact adhesive is applied to metal and linoleum separately and after a short while when glue is touch dry two materials are bonded immediately after contact with instant pressure. The latter creates great holding strength and it doesn’t require long time for drying or pressure. Once contact is made the bond is permanent. Since metal and linoleum have different ductility, bending after glueing might cause separation or crack of linoleum. Therefore, deforming the metal before attaching linoleum might be workable.

In the test group C (Figure 42), the metal sheet is bent before applying the linoleum to see if the problem in test sample B1 and B3 could be fixed. When the linoleum is attached to the sharp edges, it would still crack on the surface (sample C2). However, for the rounded surface, the linoleum could be attached to metal surface very well (sample C1).

Test group D

Except for bending techniques, I also wanted to see how linoleum would react by twisting linoleum. In the test group D (Figure 43), metal stripes were twisted before attaching linoleum with contact adhesive. The linoleum surface behaved very well on the twisted surface. The composites show the material textures of both metal and linoleum vividly with twisting curved surfaces, creating kinetic aesthetic experience.

The combination of linoleum and metal is quite interesting for the contrast between cold metal and warm linoleum. But as metal needs special finish on the surface to avoid rusting, it's complex to deal with finishing and linoleum.

Figure 41. Metal sheet bent after glueing with linoleum (test group B).

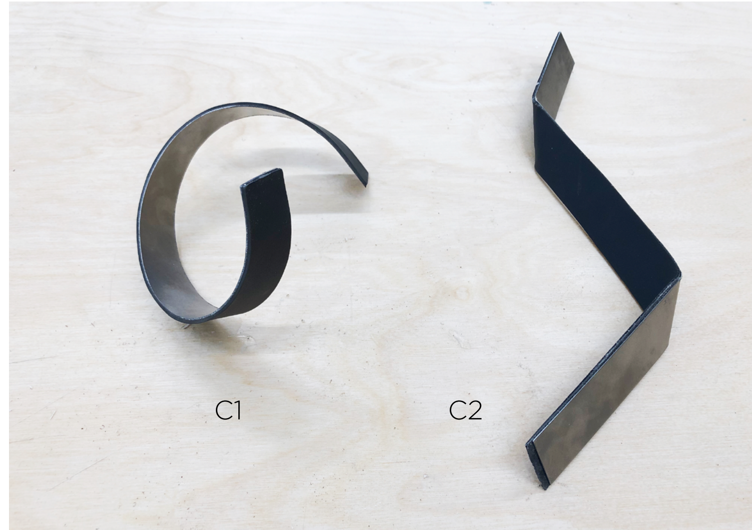


Figure 42. Metal sheet bent before glueing with linoleum (test group C).

Figure 43. Metal stripes twisted before glueing with linoleum (test group D).

Tension of Linoleum (test group E & F)

Test group E

Based on the description of Forbo Furniture Linoleum (n.d.), furniture linoleum is a unique surfacing material for furniture designs such as desks, stools, cabinets, doors and displays. Linoleum is mostly used as the surface material. But the material itself also has tensile strength to some extent and could also act as the connection between different parts, which deserves testing.

In the test group E, the tension of linoleum creates a space between the gap of wood that's split into halves (sample E1) and two layers of veneers (sample E2). Both of the test samples (Figure 44) keep some resilience and don't have enough compression strength to be stable structural elements in furniture design.

Test group F

In the test sample F, linoleum is glued partly to the bent metal sheet. The tension of linoleum acts as the structural connection between two metal pieces. And the material contrast between linoleum and metal is also very interesting. It could be transformed between two ways (Figure 45). However, this structure is not stable and could easily deform with exterior pressure.

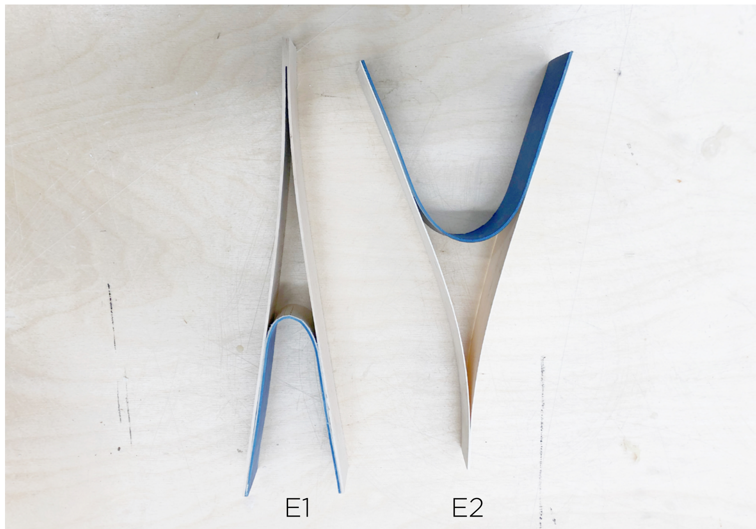
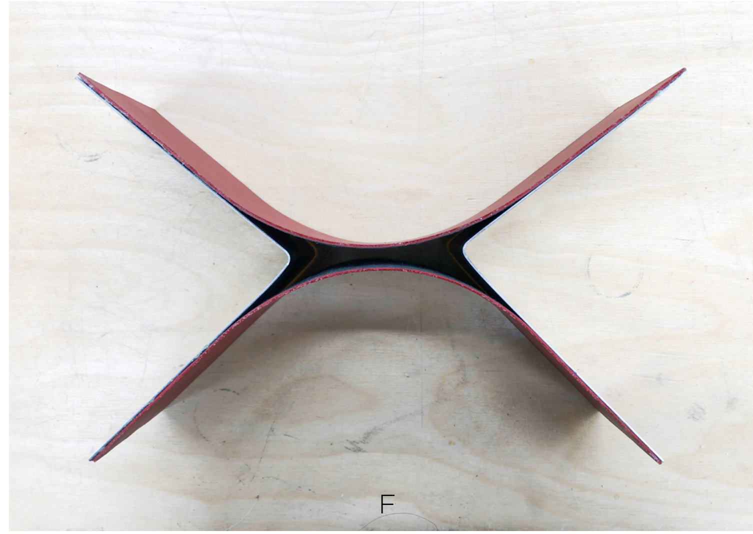


Figure 44. Linoleum connecting wood and veneers (test group E).



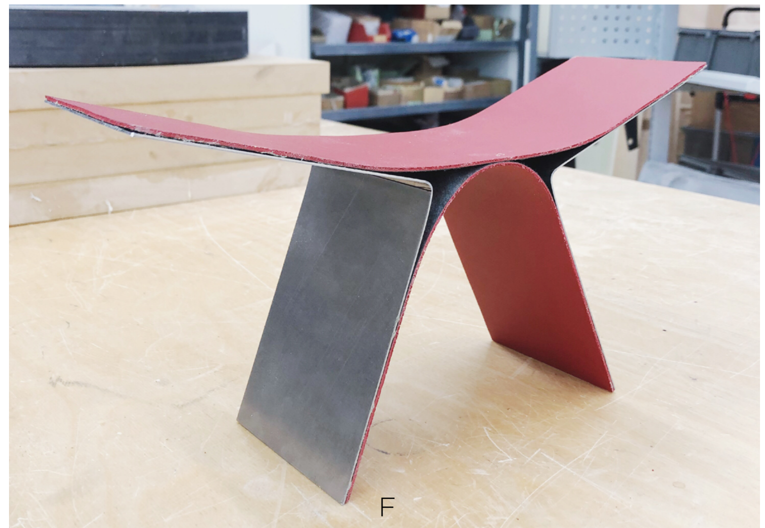


Figure 45. Test sample F that combines linoleum with metal (test group F).

3D Moulding (test group G)

As the surface material, linoleum is mostly used on the flat surface or developable surface. Developable surface is a smooth surface that can be flattened onto a plane without distortion such as semi-tubes (“Developable surface”, n.d.). Non-developable surface has double curvature, which makes it harder to apply the linoleum. The test sample B2 has shown that linoleum has some ductility but it’s not usual to see relevant examples. One of the examples is Topp 8 tray designed by Daniel Lorch in 2018 (Figure 46), which explores the boundaries of linoleum deformability. Linoleum is laminated with organic fibre on doubly curved surface. It’s meaningful to test linoleum on doubly curved surface with 3D moulding techniques.

With the guidance of Peter Albertz, the Innovation Manager from Forbo, I tried 3D press forming under the room temperature with a pair of moulds cut by CNC (Figure 47). In the test (Figure 48), two layers of linoleum were applied white wood glue on the paper backing and they were pressed by clamping between the moulds at room temperature for over half an hour. It worked out very well with deformation. Using the same pair of moulds, two more tests were made to test 3D compression moulding with various carrier materials. The test G2 combined two layers of linoleum and one layer of 1 mm thick veneer in between in a way similar to the test G1. The test G3 used contact glue between the metal mesh and two layers of linoleum.

All of the three test samples could keep the shape after the glue is dry but their resistance to deformation is different. Resistance to deformation ranks as G2 > G3 > G1. Based on the guidance from Forbo, too much pressure would leave the moulds’ structure on the linoleum surface. In the test G3 metal mesh left imprints on the linoleum surface, which showed that the carrier material in between would also affect the linoleum surface with too much pressure. As linoleum is very soft, the texture of the mould will also left on the linoleum surface with too much pressure. Of course it could also be used for design purposes rather than a problem.

It’s very important that the doubly curved mould surface is smooth. Otherwise, the linoleum might crack on the surface. Test group G has shown that linoleum has some ductility and it could be applied on doubly curved surfaces that are smooth.

Figure 46. Topp 8 tray.

Figure 47. A pair of moulds.

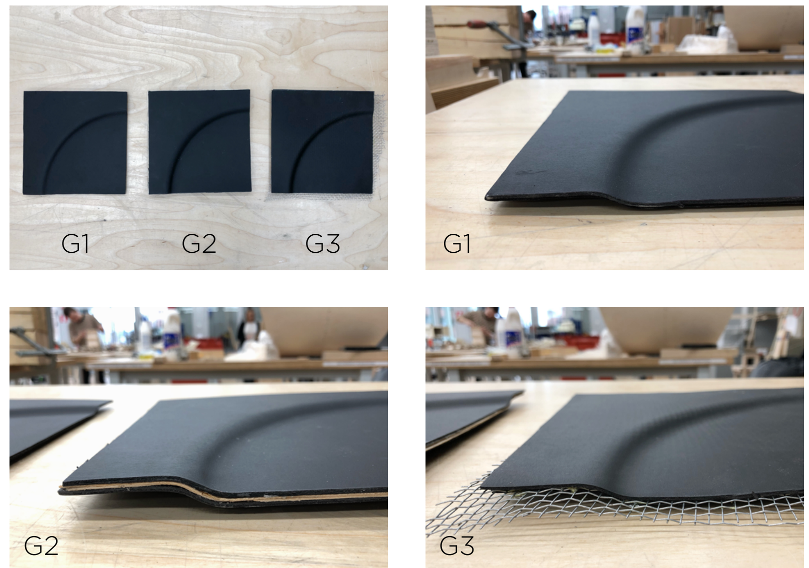


Figure 48. 3D moulding test samples (test group G).

Development of Semi-tubes (test group H, I & J)

The 3D moulding test group F have verified linoleum's ductility and ability to deform. Semi-tube material structure might be able to develop further based on it.

Test group H

In the test group H (Figure 49), the profiles of two ends for both moulds varied in size and shape. The mould H1 is curving from the top view while the mould H2 is straight. Veneers and linoleum were applied urea resin adhesive on and put in the vacuum bag for 1.5 hours at 60 °C. Test sample H1 had some cracks on the surface while test sample H2 worked out well. This test group showed that linoleum has ductility to some extent but not unlimited. The quality of deformed linoleum surface should also have relation to the mould edge diameter. If the edge diameter is bigger, linoleum surface wouldn't crack so easily with bigger bending diameter. With varying profiles at both ends and curving shape from the top view, mould H1 was more complex than H2 in comparison. Therefore, tests focusing on the curving shape from the top view should be taken to see how linoleum-veneer semi-tube material structure would react.

Figure 49. Moulds and test samples in test group H.

Test group I

The test group H is aimed to find out how linoleum-veneer semi-tube material structure would react with the mould that is curving from the top view. The mould in test group I has free curving shape from the top view (Figure 50). In the first test I1, complete veneers and linoleum were used for testing with the same vacuum pressing and thermoforming techniques. The composite was twisted in a mess (Figure 51). Inspired by clothes making techniques in the fashion industry, I modified the shape of veneers and linoleum. In the second test I2, veneers were cut following paper mould (Figure 52) to fit into the mould shape (Figure 53). The composite was very nice on the surface but one side of it was not continuous, which made the composite not stable.

Figure 50. Mould in test group I.

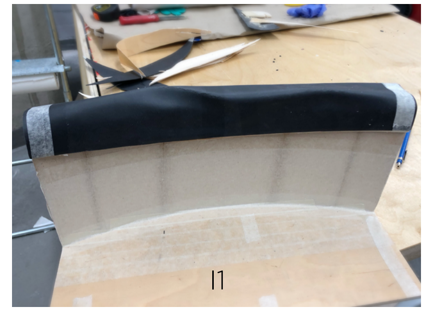


Figure 51. Test I1.

Figure 52. Material cut for test I2.

Figure 53. Test I2.

Test J

The mould in test group I has free curving shape from the top view so the linoleum and veneers need to cut away quite much to fit into the mould. Therefore, another mould is developed to minimize the cut area in test J.

From the top view, the mould in test I has shape in 3 segments that are straight, curving and straight respectively. This mould in test J has smaller challenge for veneers and linoleum than in the test group I. The linoleum and veneers still need to be cut to fit into the curing part of mould but the cut area is smaller due to the simpler mould shape (Figure 54).

Figure 54. Mould and samples in test J.

Cross Structure of Semi-tubes (test group K)

Semi-tube is very strong and light but it's only a single piece. I started to think of how to combine two or more semi-tubes to get a more stable structure (Figure 55). The semi-tube material structures that have been tested are either in C-profile or U-profile (Figure 17). A C-profile sample was cut away a part in semicircle shape (Figure 56) in order to combine with the other C-profile sample. However, the connection between these two C-profile semi-tubes in this way is too weak as a structural part.

The U-profile semi-tube has straight surfaces on both sides, which makes it different from the C-profile semi-tube. By cutting slots on the straight parts (Figure 57), two U-profile samples could be inserted with each other quite tightly (Figure 59). Slots could also be cut only in one piece of semi-tube deeper (Figure 58) and inserted with another semi-tube without cutting. The structures in these two ways have similar stability but cutting slots on two semi-tubes could help position and hide the unevenness of incision. Tests were also taken on cutting slots with different angles, which will change the angle between two semi-tubes (Figure 61).

However, the joint by inserting with the slots isn't stable enough and the semi-tubes could be disassembled easily. How to make the cross inserting structure more stable? With the question, I got some inspiration from how bamboo joint is strengthened. The base of bamboo column often bears high compressive force and thus it's easy to crack or split so one solution is to fill the cone with cement or epoxy mortar for greater stability (Minke, 2016). Since the semi-tube is hollow like bamboo, a wooden block (Figure 62) might be added between two semi-tubes to increase stability. Tests were made by glueing the wooden block as well as by using hardware to fix the wood block with semi-tubes (Figure 60). Since the wooden block was very small, it was not easy to install the hardware and the joint part wasn't stable enough. Glueing the wooden block was easier and the joint part was more stable than using hardware. From a single element to a structural part, cross structure is a breakthrough based on the semi-tube material structure.

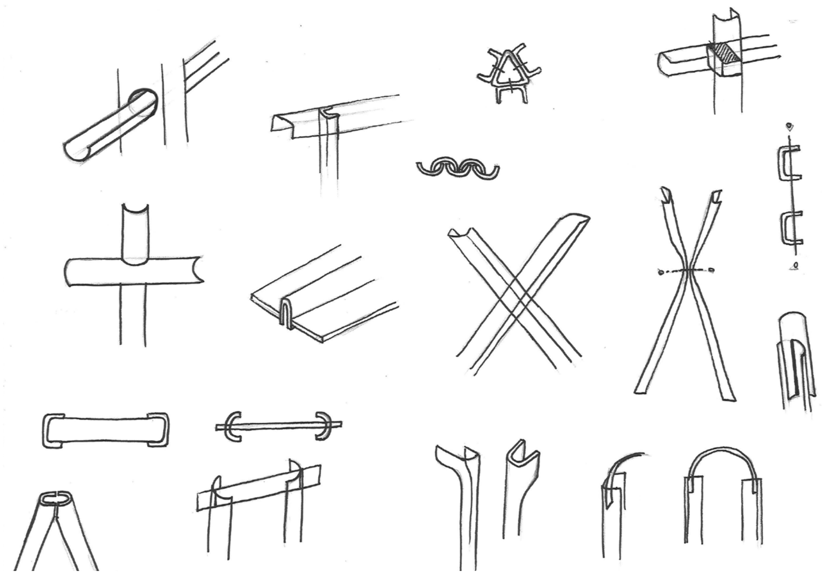


Figure 55. Drafts of connecting semi-tubes.

Figure 56. Cutting on the C-profile.

Figure 57. Cutting slots on two U-profile semi-tubes.

Figure 58. Cutting slots on only one U-profile semi-tubes.

Figure 59. Cutting slots on only one U-profile semi-tubes.

Figure 60. Cutting slots on only one U-profile semi-tubes.

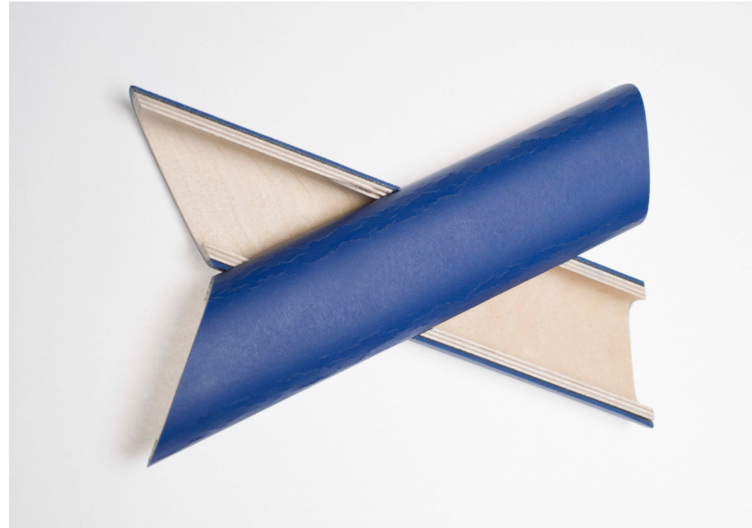


Figure 61. Cutting slots on only one U-profile semi-tubes.

Figure 62. Cutting slots on only one U-profile semi-tubes.

Reflection

Inspired by how Alvar Aalto explored new techniques and created furniture collection with standard elements, the semi-tube material structure could also be applied in different kinds of furniture. In comparison with other test samples, the semi-tube material structure has the biggest potential to adapt to various furniture structures as a standard element. Based on the semi-tube material structure, the cross structure is an advanced creation. As Alvar Aalto mentioned in the introduction to the catalogue of his exhibition, in furniture design the basic problem from a historical and practical point of view is the connecting element between the vertical and horizontal pieces and this is absolutely decisive in giving the style its character (Aalto et al., 1984). Although the crossing structure by inserting semi-tubes doesn't connect vertical and horizontal directions, it extends towards two directions in space that has the potential to be a simple but stable structural element in furniture design. Moreover, the crossing structure also gives a very special character to the from.

Crossing structure is not rare in furniture design but cross inserting structure made with linoleum-veneer semi-tube hasn't been done before. The most common example of applying crossing structure is X chair.

X Chair

According to the description in Encyclopaedia Britannica (n.d.), X chair refers to a chair with an X-shaped frame, supported by two crossed and curved supports either at the sides or at the back and front. Because of its basic simplicity, it is one of the oldest forms of chair or stool, with examples reaching back to the 2nd millennium BC. In the following several examples of X chair are listed.

Folding chair from the Bronze Age

Made of ash wood with carved patterns featuring black pitch inlay, the folding stool (Figure 63) from Guldhøj has been dated to the second half of the 1400s BC and it is the only completely preserved chair from the Bronze Age in Europe ("A folding chair from the Bronze Age", n.d.).

Folding chair with backrest from Song Dynasty

Developed from folding stools, folding chairs with backrest and armrest may date back to the Song Dynasty (the 9th century) in ancient China (Ma W., 2008). The folding chair is constructed with crossed legs that are joined at their intersection with pivot hinges and the legs extend through the back of the seat to support the backrest (Evarts, n.d.). It was very light, collapsible and portable but it's actually not stable since all the sitting load falls on the intersection part of crossed legs (Ma W., 2008). Figure 64 shows a folding round-back armchair made with hard wood and iron hardwares that dated back to the late 16th century in China for people of high ranks and now it's exhibited in Minneapolis Institute of Art.

Tric & Ginevra

Tric (Figure 65) is undoubtedly one of the most iconic products generated by the prolific and innovative creative genius of Castiglioni brothers, great masters and fathers of the Italian design ("ICON Chair", n.d.). Tric is a redesign of Thonet's B-751 folding chair out of production at that time ("Tric", n.d.).

Inspired by the already famous folding chair Tric, Ginevra (Figure 66) is a foldable armchair with a structure in bent solid beechwood, while the seat, backrest and armrests are in pressed plywood ("GINEVRA", n.d.). It was designed to be foldable. The armrests can be folded separately.

Barcelona Chair

Because of their scissors like principle, X chairs lent themselves to collapsible construction. However, not all the chairs with X legs are designed to be foldable such as the famous Barcelona Chair (Figure 67) designed by Ludwig Mies van der Rohe and Lilly Reich in 1929. According to Wikipedia, the form is thought to be extrapolated from Roman folding chairs known as the Curule Chair which was a symbol of political or military power in early Rome. In this case, X legs are designed for symbolization instead for being foldable.

The cross inserting structure originated from the test of combining two linoleum-veneer semi-tubes. Although it's not a foldable structure, its strength, stability, lightness and simplicity makes it qualified enough to be a structural part of furniture. Furthermore, the stable structure also endows the furniture work with strong character in form. Among all the furniture types, chair design is one of the most complex and challenging works. Although there have been many excellent chair designs in the world, it deserves to apply the linoleum-veneer semi-tube cross structure to chair design. Therefore, I want to design a chair with the cross inserting structure.

Figure 63. The folding stool from Guldhøj from the Bronze Age in Europe.

Figure 67. Barcelona Chair designed by Ludwig Mies van der Rohe and Lilly Reich in 1929.

Figure 64. Folding round-back armchair made in the late 16th century in China.

Figure 65. Tric chair designed by Achille and Pier Giacomo Castiglioni for BBB Bonacina in 1965.

Figure 66. Ginevra armchair designed by Achille Castiglioni for BBB Bonacina in 1979.

Prototype Making

Drafts & 3D Models

Some drafts were done to help think of the essential joints and parts on paper first (Figure 68). I had the idea of applying crossed legs to the all-purpose chair (Figure 69) and the easy chair (Figure 71). 3D models were built in computer to help think of the structure in detail as well as the proportions of different parts. The position of crossed joint is different in the all-purpose chair and the easy chair. But it's the same that the seat is fixed by two stretchers that are fixed with crossed legs and the backrest is fixed by the wooden block that are fixed with longer legs. Since the structures of the all-purpose chair (Figure 70) and the easy chair (Figure 72) are similar and easy chair is more complex to some extent, I decided to start making the easy chair prototype first.

Considering the joint detail of the backrest and longer legs, there are several ways of combination depending on if the backrest top is higher than the leg end. When the backrest top is as high as the leg end, the flaws might be obvious if they are not exactly at the same height. Therefore, there are two choices left (Figure 71) but it's hard to see the actual effects in the computer. It could be tested and decided later when it comes to the prototype. The proportions of different parts could be visualized by making 1:1 mock-up.

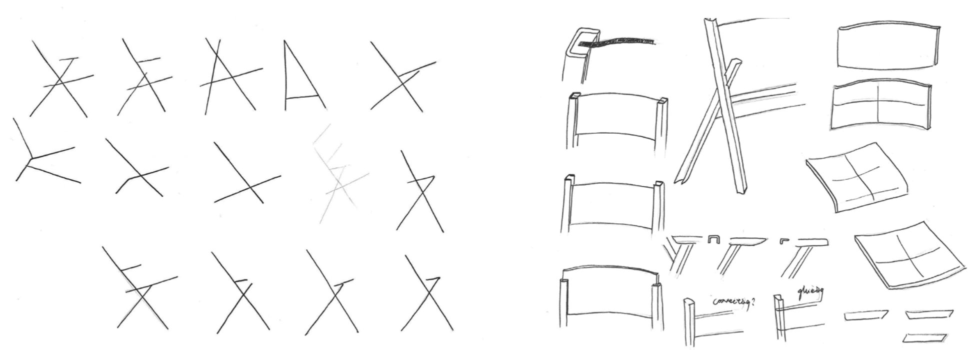


Figure 68. Drafts on paper.

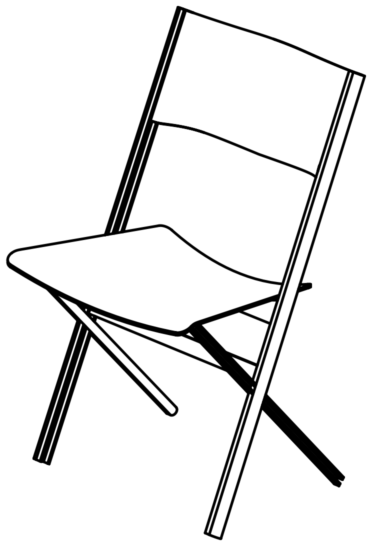


Figure 69. 3D model of the all-purpose chair.

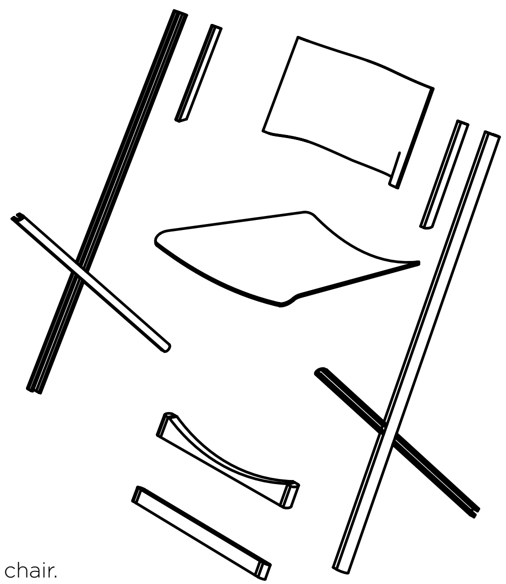


Figure 70. The exploded view of the all-purpose chair.

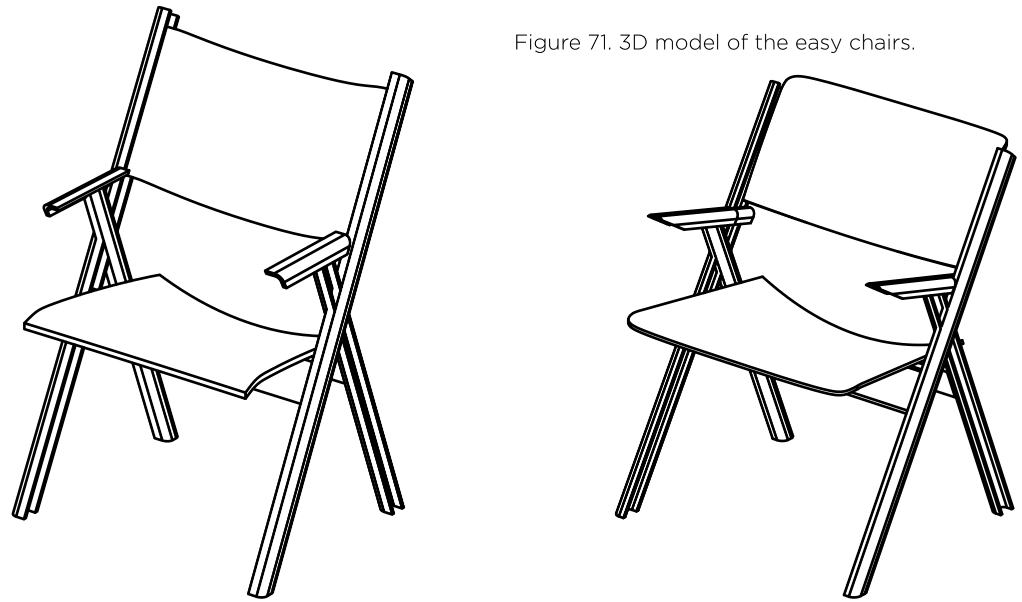


Figure 71. 3D model of the easy chairs.

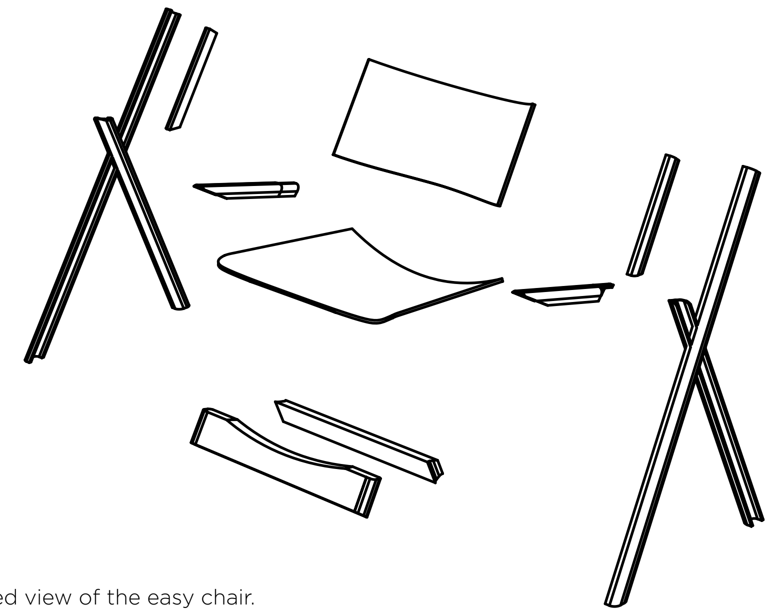


Figure 72 . The exploded view of the easy chair.

1:1 Mock-up

As it would take plenty of time to make semi-tubes, seat and backrest by laminating linoleum and veneers, the 1:1 mock-up (Figure 73) was made in a quick way with existing materials in the workshop such as solid pine wood, chipboard and thin plywood. After finishing the mock-up, I found the backrest and seat were too wide visually. The ergonomics were good when I tried sitting on it.

Figure 73. The 1:1 mock-up and sitting on it.

The First Prototype

In order to further visualize the chair idea, a more precise prototype should be made with semi-tubes and moulded seat and backrest. Based on the evaluation of 1:1 mock-up, I modified the 3D model on the computer and started to make the first prototype.

Legs

The semi-tubes used in the test sample (Figure 57 - 62) were a little bit too big for the chair legs visually. Therefore, a new mould was made (Figure 74) so that the legs could look more elegant.

The wanted width of semi-tube was only 32 mm and the edge was rounded. When the semi-tube was cut directly with table saw, it couldn't stay steadily on the table and the width of both sides would be different. Therefore, an assisting tool (Figure 75) was made to help cut each semi-tube straightly.

Cutting slots angularly for both legs that matched with each other was not an easy thing (Figure 76). Sometimes the slots of one leg might not match with that of the other leg and a gap of 2mm could be seen (Figure 77), which also caused instability in the crossing structure. Extra legs were made for backup.

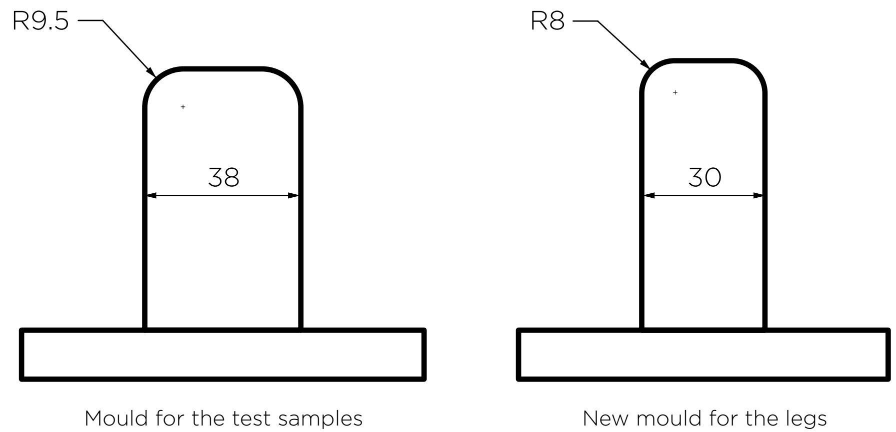


Figure 74. Mould for the test samples and new mould for the legs.

Figure 75. An assisting tool made for cutting legs straightly.

Figure 76. Slots that matched well.

Figure 77. Slots that didn't match well.

Backrest & Seat

I tried two ways of making the backrest and seat. One way was to clamp all the veneers and linoleum (Figure 78) after applying glue. They failed to form the shape properly but the first backrest and seat could still be used for testing.

The second backrest and seat were made in the vacuum bag system (Figure 79). They seemed to work well before taking away the masking tape that helped prevent the linoleum surface from scratch or glue.

Figure 78. Clamping materials on the mould.

Figure 79. Backrest and mould in the vacuum bag.

Armrests

When it comes to the design of armrests, more aspects should be considered including the profile shape and size, cuts of both ends, tilting angle, length and connection with the other parts. The profile shape of the armrests could be in U profile, L profile or flat (Figure 80) and the size of the profile could vary in height and width. Cuts of both ends could have different shapes (Figure 81). The armrests could be either parallel to the ground or parallel to the seat. The connection between the armrests and legs have two different ways (Figure 82). The profile shape and length is relevant to how armrests connect with legs. There Tests were made considering all the aspects mentioned above (Figure 83). Connection 1 is more stable but it could also make the joint look messy from the aesthetic aspect. I decided to test Connection 2 first (Figure 84), which was also quite stable but may be suitable for only supporting elbows. Compared with U profile or flat shape, armrests in L profile could hide the joint part that might not look so nice as well as make the chair not closed visually. Straight cuts at both ends would make the armrests a bit stiff while the cross legs are tilted so I chose to have tilted cuts at both ends.

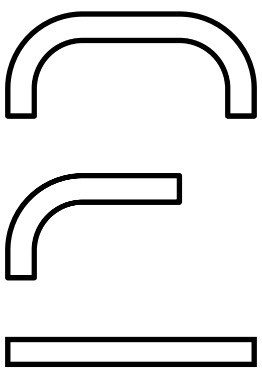


Figure 80. Different profiles for armrests.

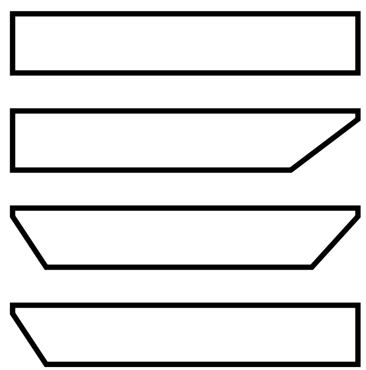


Figure 81. Cuts in different shapes at the end.

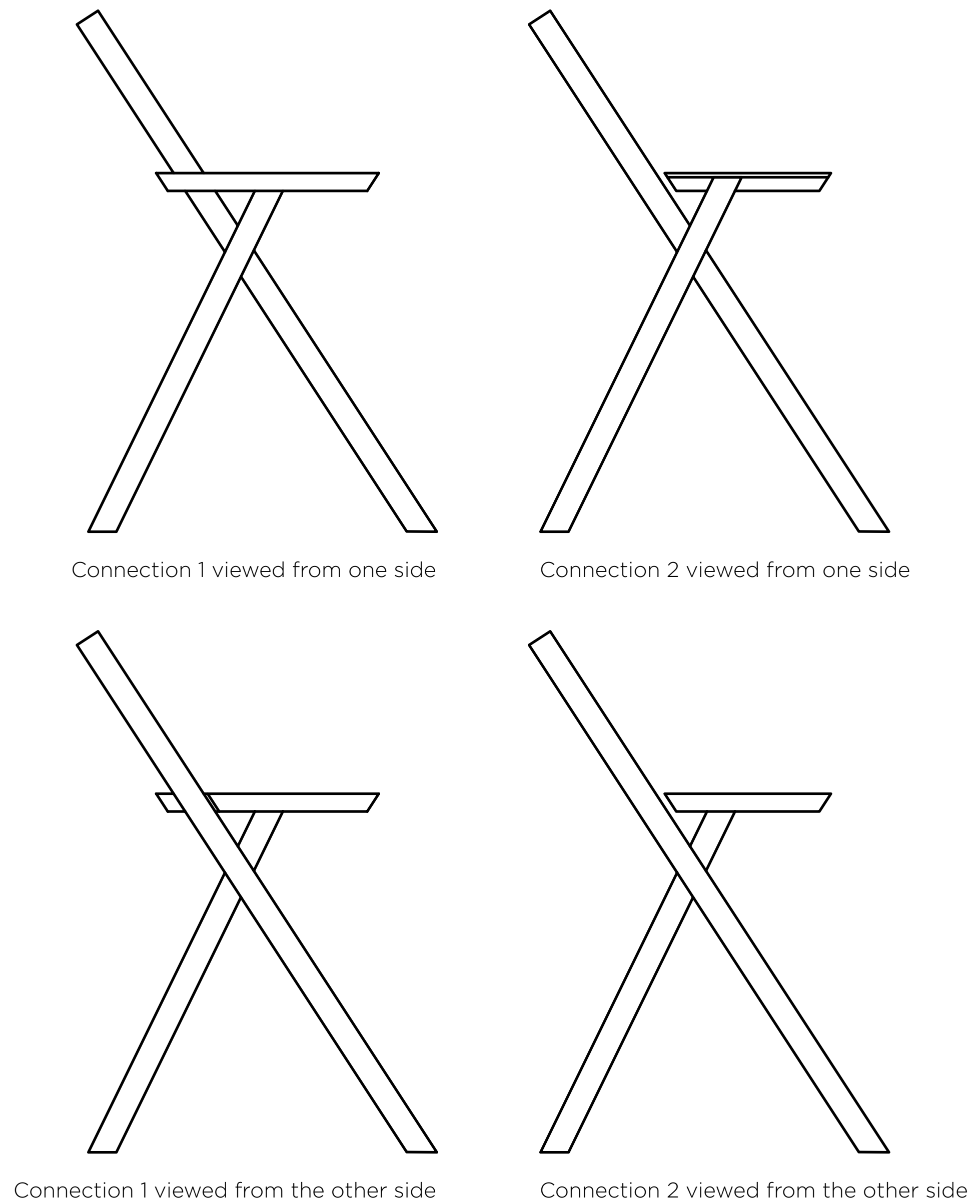


Figure 82. Different connections between the armrests and the legs.

Figure 83. Different tests on the armrests.

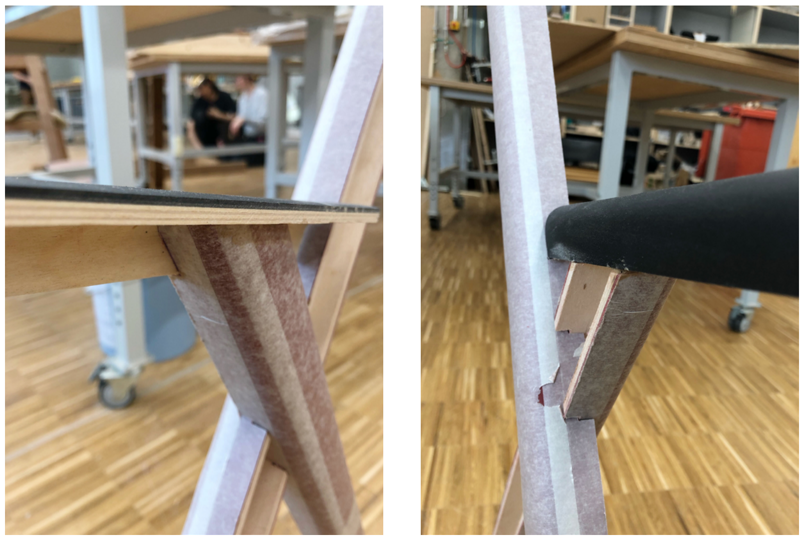


Figure 84. Test on Connection 2.

Adjust Proportions

By covering the top of front legs and the backrest with white paper and adjusting paper, different proportion combination effects could be visualized (Figure 85). A cardboard was cut in the seat size and fixed with other parts with tape, which also helped check if the seat size and proportion was suitable or not (Figure 86).

The first backrest and seat were cut based on the visualization result of last step. All the parts were fixed with clamps or supported (Figure 87). The 1:1 front and side view of the computer model was printed out on paper. Fixing all the parts and printing out the 1:1 model view helped a lot to evaluate the general form and proportions of the chair (Figure 88). Different shapes and the tilted angle of the armrest were tested again. After discussion, the armrests, the second backrest and the second seat were cut for the final prototype.

Figure 85. Adjusting white paper to test different proportion combination.

Figure 86. Using cardboard to test the seat size and proportion.

Figure 87. All the parts were fixed to check the overall proportion.

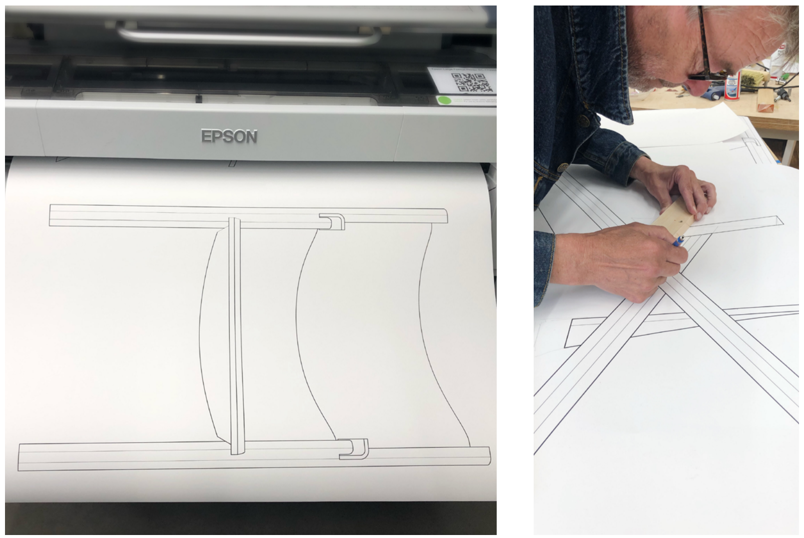


Figure 88. Discuss with the printed 1:1 model view.

Stretchers

In the coat rack design, solid wood stretchers are glued directly to the legs in U-profile and it's very stable. The same method could be used in combining the front solid wood stretcher and two front legs for the easy chair. But the situation is different for combining the rear stretcher and two rear legs. As linoleum is water-proven, the rear stretcher and two rear legs couldn't be glued in the same way as the front stretcher and two front legs. Therefore, different ways of connecting were tested (Figure 89). Cutting groove could help glueing but the groove were not accurate enough and the glueing surface was too small for the sitting load. Groove also weakened the thickness and strength of semi-tube. Therefore, the groove shouldn't be made on the surface and glueing wasn't a good way of fixing the stretcher to the legs. Different hardware was used for testing (Figure 90). Compared with embedded nuts (joint 2), cross-hole nuts (joint 1) made the joint much stable. Therefore, cross-hole nuts, washers and screws would be used for combining the stretcher and two rear legs in the prototype.

Since the seat has double curves on the surface, it's not easy to make stretchers perfectly matched with the bottom of the seat. Firstly, the legs, the seat and the stretchers were fixed with tape and clamps (Figure 91). Then curves were drawn on both sides of stretchers with the assistance of self-made tools that followed the curves on the seat bottom (Figure 92). Following the curves drawn on the stretchers, extra part was planed away with hand planer.

In order to visualize different proportions of the front legs and the backrest, I covered the top of front legs with white paper and moved it (Figure 93) until I found a good visual balance. It was when the top of the front legs was 30 mm longer than the top of the backrest that the chair looked good.

The front legs had the final cut and they were glued to the rear legs with wooden blocks. Then the backrest and the front stretchers were glued with the front legs at the same time with the rear stretcher fixed by hardware to the rear legs (Figure 94).

To make the stretchers fit to the seat well, sanding of stretchers is indispensable. It took a long time to sand the stretchers but it was still an easy way for making prototype. The last step was glueing seat to the stretchers and using clamps to fix them (Figure 95).

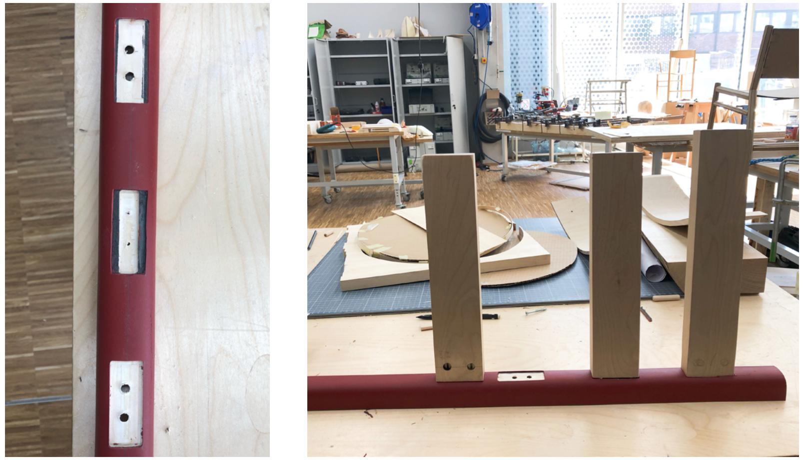


Figure 89. Different tests on combining the stretcher and the leg.

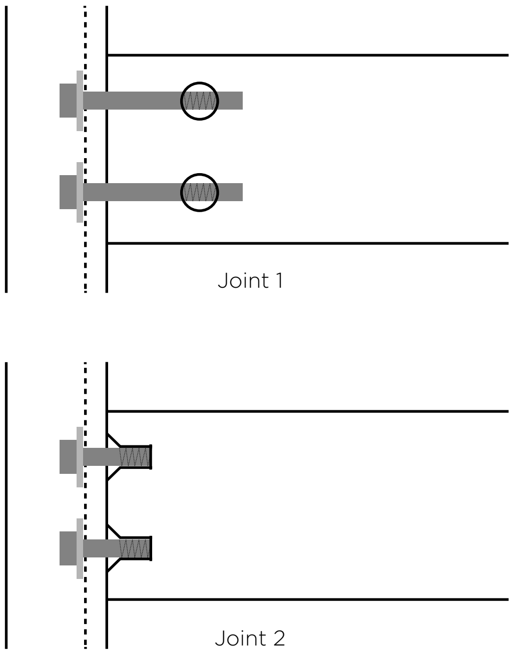


Figure 90. Two ways of connecting legs and stretcher with hardwares.

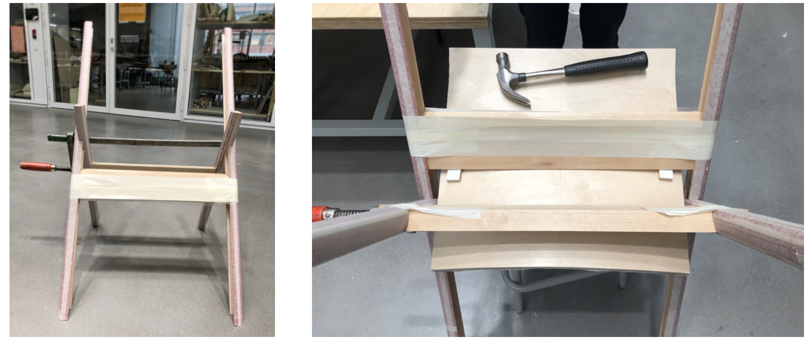


Figure 91. Fixing the legs, the seat and stretchers.

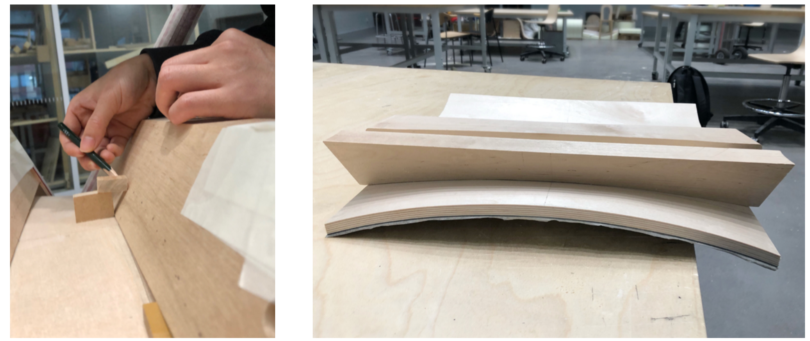


Figure 92. Drawing lines on the stretchers and plane the stretchers.

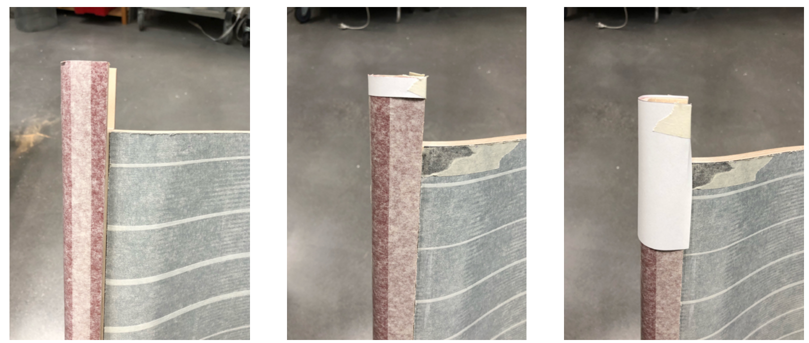


Figure 93. Test different proportions of the front leg tops and the backrest top.


Figure 94. Glue the backrest and front stretchers with other parts at the same time.

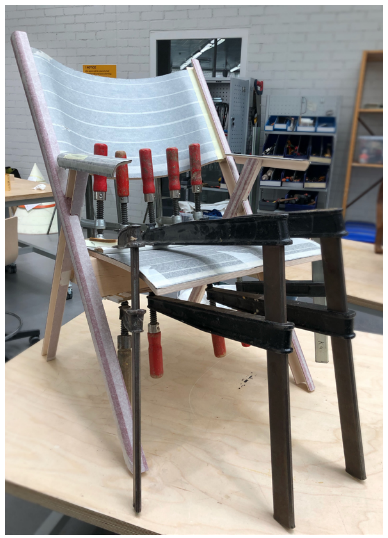


Figure 95. Glue the seat to the stretchers after planing the stretchers.

Reflections

After taking away the masking tape on linoleum surface, I found there were some bumps on the seat surface and legs and uneven pattern on the backrest surface. The cause of bumps on the seat surface (Figure 96) might be too much glue, uneven pressure from the vacuum bag on linoleum or uneven paper backing. As glue applied was quite little and thin, the bumps probably resulted from the uneven pressure and uneven paper backing left on the linoleum. The cause of unevenness on the backrest (Figure 97) might be lack of paper backing and rough patterned backrest mould.

Despite the deficiency mentioned above, the ergonomics of this easy chair was comfortable after testing with people of different height from 160cm to 180 cm. It's also very stable from the structural aspect. Proportion of the side view was very good (Figure 98). But the whole chair looked a little cumbersome from the front view, which might be attributed to the sizes of backrest and seat as well as the relationship between the backrest and front legs. There were also other details that needed to be reconsidered carefully. Therefore, I wanted to develop the chair better by making the second prototype based on the first prototype.

Figure 96. Bumps on the seat.

Figure 97. Unevenness on the backrest.

Figure 98. Side view of the first prototype.

Figure 99. Front view of the first prototype.

Figure 100. Perspective view of the first prototype.

The Second Prototype

Fixing unevenness on backrest and seat

The seats and backrests made for the first prototype didn't have smooth surfaces (Figure 96 & 97). As analysed above, the bumps on the seat might result from the uneven paper backing and uneven pressure from the vacuum bag.

Since the seat and backrest didn't have sharp edges like the semi-tubes, the linoleum might work well without soaking in hot water or removing the paper backing. Therefore, the third seat and backrest were made without soaking linoleum in hot water and without taking away the paper backing. Moreover, a piece of aircraft plywood was put between the seat linoleum and vacuum bag while a piece of aircraft plywood was put between the backrest linoleum and the mould. The surface of both seat and backrest was much better than the previous ones. However, a small wood chip on the seat surface left a groove on the linoleum surface (Figure 101). Following Forbo Linoleum's instructions of filling holes (personal communication, July 2, 2019) via email with Peter Albertz, I mixed black linoleum powder and white glue and filled in the groove for several times (Figure 102). The groove was filled but it's still visible on the seat surface. This way of repairing holes might have a good result for linoleum on the floor which occupied much bigger surface than that on furniture.

Figure 101. The groove left on the seat surface by a small wood chip.

Figure 102. Fill the groove with the mixture of white glue and linoleum powder.

There were two ways of fixing the problem completely. One way was to attach another piece of linoleum on the seat. Another way was to remove the previous linoleum and attach a new piece of linoleum on plywood.

Then I tested if another piece of new linoleum could be attached to the linoleum. 4 pieces of linoleum of the same size were cut. Two of them were sanded on the surface to remove the water-proven surface finish (Figure 103). Then they were applied respectively with white glue and urea resin adhesive. The other two pieces were put on them and given even pressure. Both of them proved to work well. It's workable to attach linoleum on the other piece of linoleum. But it would make the seat thicker and it also took much time to sand the linoleum surface.

Another way was to remove the previous linoleum and attach a new piece of linoleum on plywood. It definitely would work because both plywood and linoleum paper backing were absorbent to water. After removing the previous linoleum, urea resin adhesive was spread on the seat surface and a new piece of linoleum was put on it. They were put in the vacuum bag with a piece of aircraft plywood in between. It worked out well but it also took a lot of time to remove the glued linoleum.

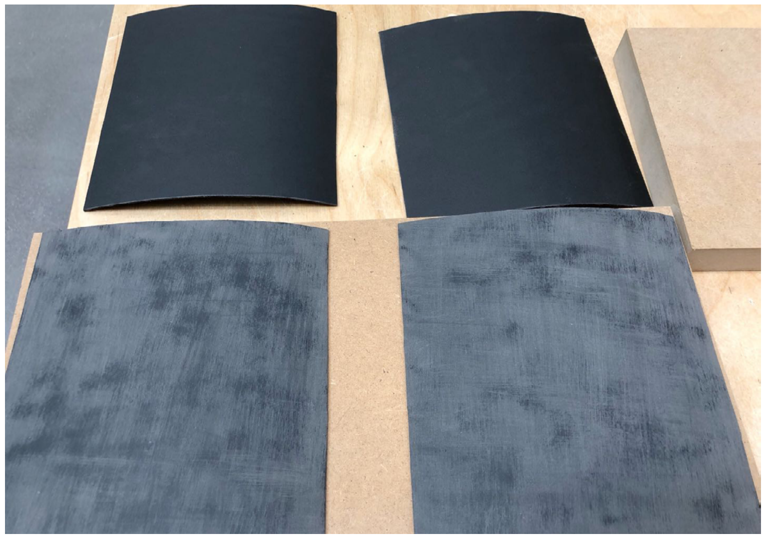


Figure 103. Four pieces of linoleum ready for testing.

Other Improvements

Apart from the seat and backrest surface, I've also noticed other parts that need to be improved (Figure 104).

Considering from the visual effect of front view, the backrest looks "heavier" than the seat in the first prototype. One way could be diminishing the backrest height. The other way is to adjust the relation of backrest and front legs so that the backrest top is higher than the front leg top. One problem with the cross legs is that the slots are not cut very accurately probably because of insufficient tests. Moreover, the tilt angle of the seat is not enough and the seat front could have a cut angle for more comfort. For the armrests, the supporting area needs to widen and tilt angle needs to increase with the tilted seat. Last but not least, the front stretcher connecting seat and front legs is quite visible from the front view and it needs to look lighter by cutting in a different angle.

In order to see a good proportion, white paper was covered on the backrest top and front leg top and it was moved up and down. When the leg top is 7 cm lower than the backrest top, the proportion looks pretty good (Figure 105).

Figure 105. Cover the backrest and front legs with paper to check proportions.

Figure 104. Parts that need improvement in the first prototype.

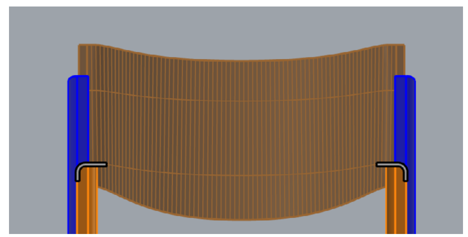
Digital Model and Scale Model

As mentioned above, the front leg top could be lower than the backrest front so that the whole chair looks more slender visually. There are two ways of combining the backrest and front legs and two different 3D models are built in the computer (Figure 106). Considering the delicacy of joint, I decided to continue joint 1 shown in Figure 106.

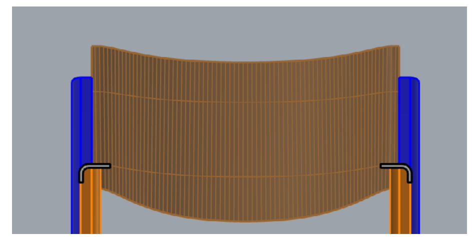
As the backrest in the first prototype looks much heavier than the seat, the backrest height in the second prototype diminished by 20 mm compared to that in the first prototype. There is a typical recommendation concerning distance between the seat surface and bottom of backrest which should be around 100-200 mm. As increasing seat tilt angle makes the seat bottom lower, distance between the backrest bottom should also decrease to ensure what's recommended for the backrest dimensions.

The armrests are widened by 10 mm. As for the tilt angle of armrests, I'm not so sure how to refine in the digital model but I would test it with the physical objects.

Thanks to the 3D printing technique, the 1:5 scale mock-up was made easily and accurately to see the proportions (Figure 107). However, it should be noted that our perspectives change when we look at the 1:5 model (Figure 107) and the 1:1 modified prototype (Figure 105). The most noticeable difference is the dimension sense of seat and backrest. In the 1:5 scale model, we overlook it so the seat looks bigger compared to the backrest. But in the 1:1 modified prototype, the height of chair makes us notice the backrest more than the seat.



joint 1



joint 2

Figure 106. 3D models are built in the computer.

Figure 107. 1:5 scale mock-up by 3D printing.

To see the real effect of the chair, the 1:1 side view was printed out with paper and the outline was cut out after glueing paper to the cardboard (Figure 108).

Figure 108. The 1:1 side view printed.

Cutting Slots on Legs

In the first prototype, the failure rate of cutting slots angularly for both legs that matched with each other is quite high (Figure 77), which might result from insufficient tests. During the process of making the second prototype, I have done plenty of pre-tests (Figure 109) with different data groups that are accurate to 0.1 mm on the numerical control table saw machine (Figure 110). A group of data was found to be most suitable and the legs were all cut in a good way.

Figure 109. Plenty of pre-tests done before cutting the semi-tube legs.

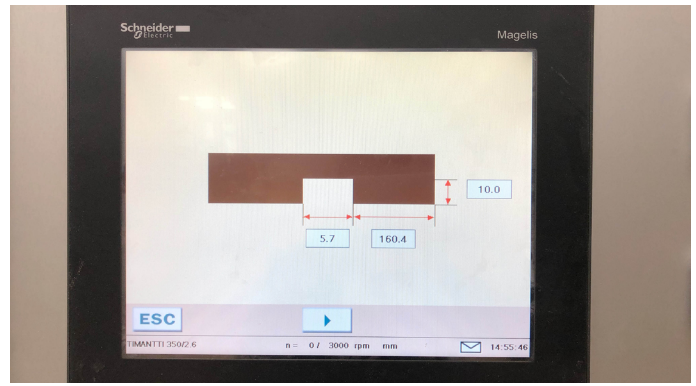


Figure 110. Display and operation screen on the table saw to cut slots.

Backrests

As the slots on two sides of the backrest do not go all the way through it, I had to use the table saw machine for neat cut edge and then the knife for delicate cut. The backrest got destroyed while I was cutting the slots on the surface due to lack of stability (Figure 111). Two more backrests were made in case of any other accidents. More support was added when I cut the backrests again on the table saw machine and it worked out well (Figure 112). Then the backrest was fixed with clamps to cut away extra part with knife (Figure 113). In order to make the joint accurately, plenty of tests were made before cutting slots on the long wood blocks that connect the backrest and two front legs (Figure 114).

Figure 111. Backrest got destroyed.

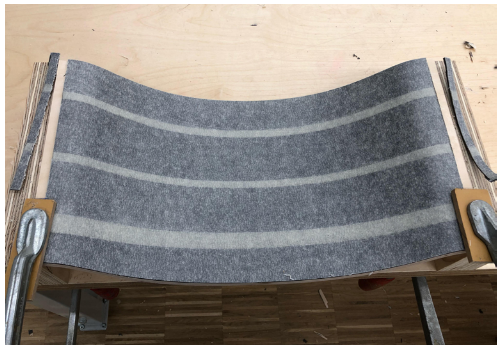


Figure 113. Cutting away extra part with knife.

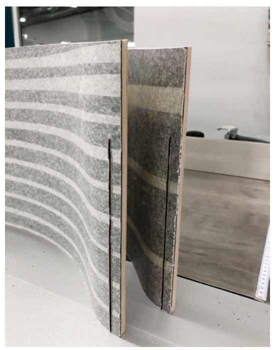
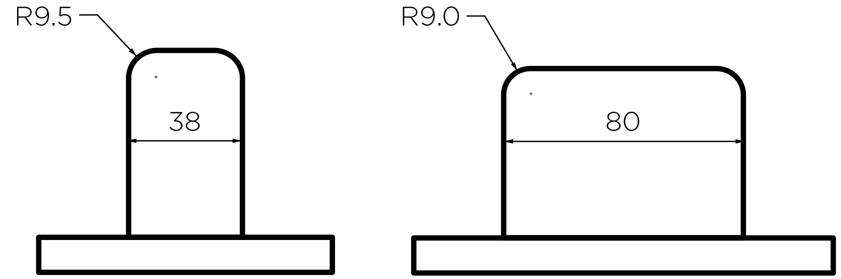


Figure 112. After cutting slots.

Figure 114. Tests on cutting slots.

Armrests

During the ergonomic test of the first prototype, people felt that there is not enough supporting space for elbow. Therefore, a new mould was made for widen the armrest width (Figure 115) for the second prototype. Moreover, the armrest length needed to be shortened so that it could connect to the rear leg more stably. And the tilted angle of armrests needed to be reconsidered for better ergonomic and visual effects. Considering the functional and aesthetic aspect, different lengths and tilted angles were tested after being fixed with legs in contrast with the first prototype as well as the printed side view of the second prototype (Figure 116).



armrest mould for the first prototype
armrest mould for the second prototype

Figure 115. Profile of armrest mould for the first and the second prototype.

Figure 116. Testing armrests.

Seat

In the first prototype, the difference between the front end and the rear end was a bit too much. With the perspective visual effect, the front end seemed much bigger than the rear end, which made the whole chair unbalanced. Therefore, boards in different sizes were cut for testing for the second prototype (Figure 117). Finally, the seat of 8mm difference was chosen as it brought a balanced proportion for the whole chair.

Edge Finishing

The linoleum didn't have special edge finishing in the first prototype, which made it easy to get damaged with hit. For the second prototype, I used sandpaper to polish the linoleum edge (Figure 118) as edge finishing type A in Figure 11, which would help protect it.

Ergonomic Test

After assembling all the parts, I asked people of different height to try sitting on it. One girl is around 163cm and one boy is around 185cm (Figure 119). Both of them felt the chair was very comfortable in ergonomics and the chair was lighter than expected.

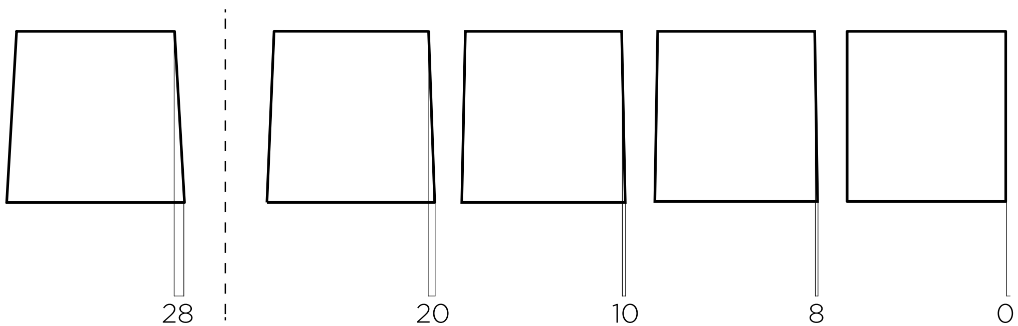


Figure 117. Seat size difference of the first prototype and the second prototype.

Figure 118. Using sandpaper to polish the linoleum edge.

Figure 119. Ergonomic tests.

Footpads

Footpads are important for a chair. For the chair prototypes I designed with semi-tubes, it's hard to find suitable footpads in the shops as the U-profile leg profile is very rare. Therefore, I decided to design the footpads especially for these two chairs and use 3D printing techniques. There were two types of footpads shown in Figure 120. Footpad 1 surrounded the whole leg profile which was very stable but looked very rough. In comparison, footpad 2 was more elegant and could be a nice detail while it also functioned well. The footpads need to be printed with flexible materials so that they could fit the U-profile legs but won't cause damage. The testing process is iterative because of the accuracy up to 0.1 mm (Figure 121).

Reflection

The second prototype has gained the proportions much better than the first prototype although the actual widths of the whole chairs are the same. The second prototype looks lighter than the first one mainly because the relation between the front leg and the backrest has changed. In the first prototype, I wanted to emphasize the cross structure so the front leg top was higher than the backrest top, which sacrificed the whole chair proportion to some extent. For the second prototype, I considered more about the whole proportion and made the front leg top lower than the backrest top, which makes it lighter visually. Decreasing the backrest thickness and stretcher height also makes it lighter. The structure is basically the same as the first prototype, but diminishing the armrest length lowers risks to some extent in the second prototype. As for the ergonomic aspect, the second prototype is more comfortable with more tilted seat. More details such as the linoleum edge finishing and footpads are also considered. By making the second prototype, I get more familiar with relevant techniques and enhance my prototype making skills.

However, there are still some problems to be solved in the future development of applying linoleum in furniture design. For example, it was after the tape on linoleum was all removed that I found the overlap of tape left shallow dents on the linoleum surface of the seat and backrest. When I checked the seat and backrest before assembling the chair, I only took away a single layer of tape and didn't notice the overlap. It is most likely to be attributed to the different tape I used.

Of course it could also be used for design purpose to create certain pattern. Nevertheless, if the surface is expected to be smooth, there are several ways that are available for those who make prototypes in workshops. Tape may be applied after the veneers and linoleum are laminated for protecting the surface during subsequent process. But before putting linoleum into the vacuum bag, it still needs something such as thin plastic film to protect the surface from being polluted by the glue. The other way is to apply thinner masking tape or the tape big enough for the whole surface, which is especially intended for protecting surface. These are what designer could do while making prototypes with furniture linoleum in the workshop that is not tidy of high standard. An easier solution for designers might be that the furniture linoleum is attached with a protective film by the manufacturer. In this way, the designers don't need to worry about the problem of glue pollution, scratches or dents on linoleum surface during the complicated prototyping process.

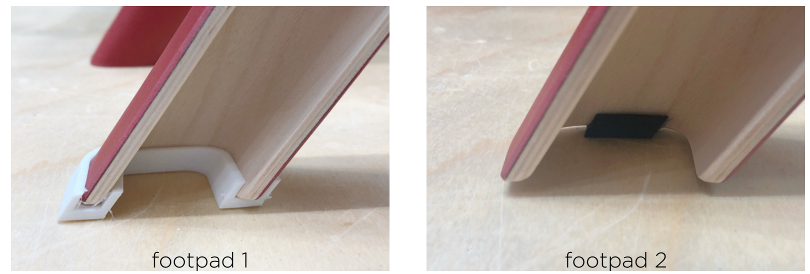


Figure 120. Two types of footpads.


Figure 121. Tests pieces of 3D printed foodpads.

CONCLUSION

Among various surface materials in furniture design, linoleum has its unique features and characters. First of all, linoleum is environmentally sustainable as a synthetic material made with natural nontoxic ingredients. Secondly, furniture linoleum has such a warm tactile feeling that makes people comfortable. Moreover, it's durable and easy to clean. However, the application of furniture linoleum requires strict conditions, including clean manufacturing environment, special equipment and skilled workers. Compared with floor application, furniture linoleum demands more care and attention to prevent scratches and cracks. Any hit could lead to unpleasant results on the surface. As furniture linoleum is mostly used on the flat surfaces, I was curious how it would be to apply linoleum on the sharply curved surface such as the semi-tube. It drives me to explore the possibility of linoleum in furniture design. I challenged myself to experiment with different types of structures with linoleum and other materials.

I started with a series of controlled tests on semi-tubes laminated by veneer and linoleum to see how the strength of the semi-tube material structure would change and how the surface would react with different variables. The most valuable finding of the preliminary tests is how to apply linoleum on the curved surface in a proper way. For example, pretreatment of soaking linoleum in hot water and removing away the paper backing could help prevent linoleum surface from cracking especially when the mould edge is sharp. By applying semi-tubes in the design of a coat rack and looking up how Alvar Aalto designed series of furniture, I realized the countless combination possibilities of basic standard elements in furniture design. Therefore, I decided to explore more into the basic elements composed of linoleum and other materials, mainly wood and metal that are mostly used in furniture design. Techniques such as compression moulding and 3D moulding were used in the tests of combining linoleum and wood. Common cold deforming techniques were used in the tests of combining linoleum and metal. It was a very interesting process to explore from material to standard elements. Some test samples combining linoleum with veneer or thin wood don't have enough structural strength as parts of furniture. The test samples combining linoleum with metal have enough strength but it's a problem how to deal with metal surface finish that avoids rusting and linoleum simultaneously. The tests developing from semi-tubes are very promising but it remains further practice to apply in furniture design.

Among all the tests, I continued with the semi-tube material structure laminated by linoleum and veneer considering its potential as a standard element in furniture design. The semi-tube material structure has certain compressive strength and it's very light. The semi-tube material structure could show the elegant beauty of both wood and linoleum. The cross structure inserted by two semi-tubes was found to be stable and light so I used it in the design of easy chairs. To design an easy chair and make prototypes, I have been confronted with many unexpected obstacles but I've tried my best to figure out possible solutions. Two prototypes were made after considering all the aspects. Developed from the first prototype, the second prototype has better ergonomics, structures and proportions and it's lighter in weight. From the whole thesis project process, I learned to develop from simple sketches through successive experiments and improvements to prototypes.

The next challenge for me might be how to develop the furniture made with linoleum that is convenient for mass production and becomes socially acceptable.

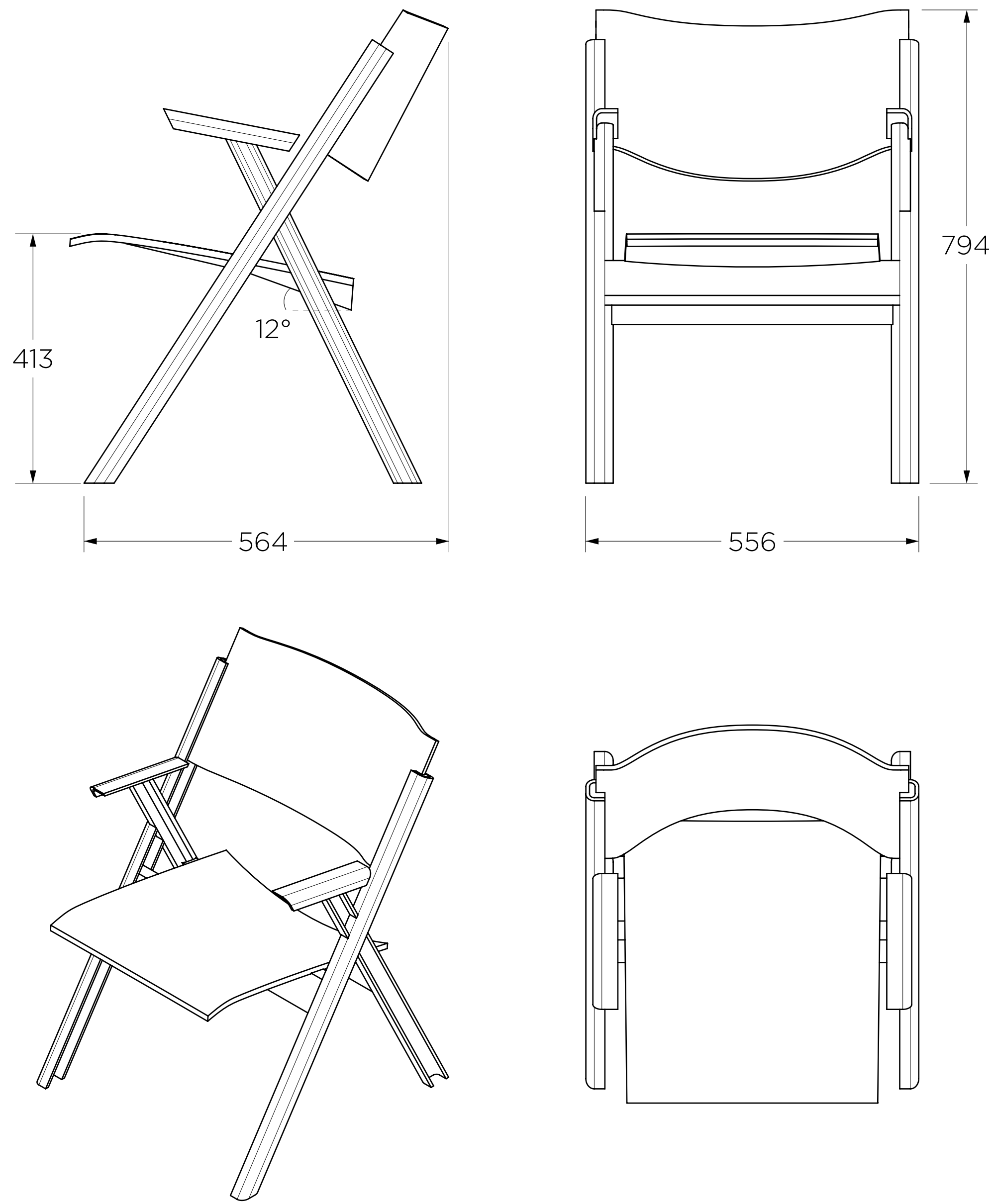
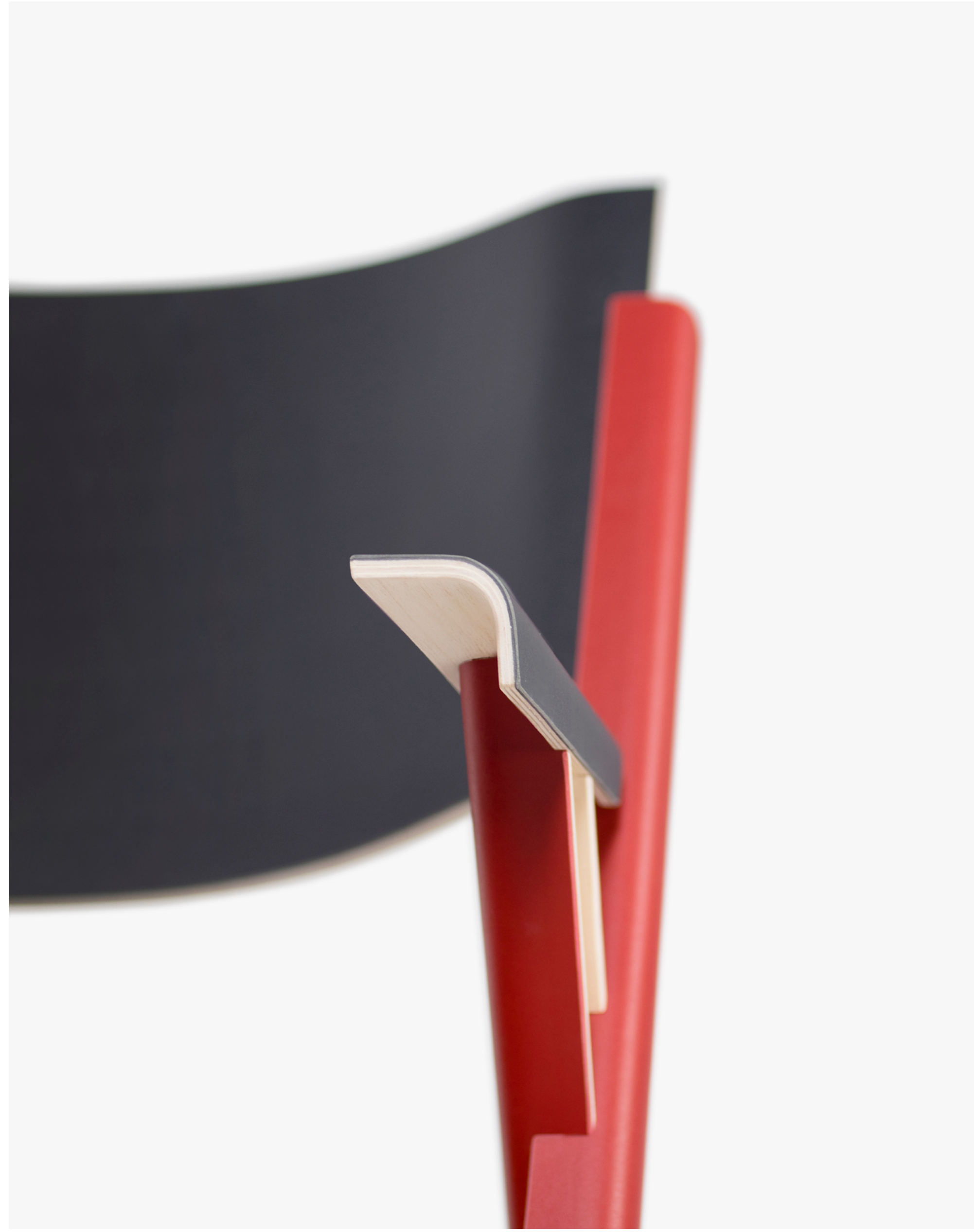


Figure 122. Technical drawings of the second prototype.



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Acknowledgement

Ville Kokkonen	Supervisor & advisor
Martin Relander	Advisor
Tatu Vuorio	Wood workshop master
Mikko Ristimäki	CNC workshop master
Mirja Niemelä	Designer in residence
Mervi Palva	Study coordinator
Marijke Griffioen	Senior designer at Forbo
Peter Albertz	Innovation manager at Forbo
Families & Friends	Love and support

Department of Design Express Grant

Kipsari Grants of TOKYO student association

School of Arts, Design and Architecture of Aalto University

jinghuazeng.com